DOCUMENT RESUME

ED 106 752	CS 001 770
TITLE	Report of the Conference on Visual Information Processing Research and Technology (Columbia, Maryland, June 10-21, 1974).
INSTITUTION	National Inst. of Education (DHEW), Washington, D.C.
PUB DATE	75
NOTE	219p.
EDRS PRICE	MF-$0.76 HC-$10.78 PLUS POSTAGE
DESCRIPTORS	Conference Reports; *Eye Movements; *Information Processing; Reading; *Reading Processes; *Reading Research; Reading Skills; Research Needs; Research Problems; *Visual Learning; Visual Perception
IDENTIFIERS	*National Conference Visual Information Processing

ABSTRACT

Chapter 1 of this report, "Introduction and General Recommendations for Eye-Movement Research and Instrumentation," discusses research priorities; encouraging and supporting theories, models, or simulations of information processing; and improved instrumentation in the field of visual information processing. Chapter 2, "Summary of Specific Recommendations," presents specific recommendations for the following four clusters: (1) reading texts, pictures, and other graphic displays; (2) processing television displays; (3) eye-movement research; and (4) instrumentation and instrumentalities. Chapter 3, "Specific Recommendations for Directions in Eye-Movement Research," recommends eye-movement research that explores the moment-to-moment information intake and processing mechanisms in the encounter of an individual with text, pictures, and other static graphic display; suggests research that explores the intake and processing of dynamic visual information as it is received from television; and argues the general value of eye movement research. Chapter 4, "Instrumentation and Instrumentalities," has four parts relating to the following areas: research, management, review, and support; instrumentation development; facilities dissemination and establishment; and priorities. (WR)

REPORT

OF THE CONFERENCE ON

VISUAL INFORMATION PROCESSING RESEARCH AND TECHNOLOGY

TO THE

NATIONAL INSTITUTE OF EDUCATION

Samuel Y. Gibbon, Jr. (Chairman), The Children's Television Workshop
Mary Carol Day, Harvard University
Edward A. DeAvila, Bilingual Children's Television
Barbara N. Flagg, Harvard University
John J. Geyer, Rutgers University
Marshall M. Haith, University of Denver
Julian Hochberg, Columbia University
Kenneth G. O'Bryan, The Ontario Institute for Studies in Education
Juan Pascual-Leone, York University
David Sheena, Whittaker Corporation
Sheldon H. White, Harvard University

Copies of this document may be purchased from the Education Documents Reproduction Service, Post Office Box 190, Arlington, Virginia 22210. Please use the identifying number CS-001770, and enclose $10.78 + .42 postage for hard copy or $.76 + .18 postage for microfiche copy.

U.S. Department of Health, Education and Welfare

CONTENTS

Page

PREFACE i

FOREWORD v

CHAPTER 1. Introduction and General Recommendations for Eye-Movement Research and Instrumentation.............. 1-1

I. Research.. 1-3
II. Theory.. 1-6
III. Instrumentation...................................... 1-8

CHAPTER 2. Summary of Specific Recommendations............. 2-1

A. Reading texts, pictures, and other Graphic Displays. 2-1
B. Processing Television Displays...................... 2-2
C. Other Applications of Eye-Movement Research......... 2-3
D. Instrumentation and Instrumentalities............... 2-4

CHAPTER 3. Specific Recommendations for Directions in Eye-Movement Research.. 3-1

I. Text, Pictures and Graphic Displays.............. 3-3
A. Text... 3-4
B. Pictures and Graphic Displays.................. 3-25
II. Television....................................... 3-31
A. Analysis of the Medium........................ 3-33
B. Properties of the Medium and Processes of the Viewer.................................. 3-35
C. Television as a Medium of Instruction.......... 3-41
D. Television and Special Groups.................. 3-48
III. Other Applications of Eye-Movement Research....... 3-52
A. The Relation Between Developmental Changes and the Intake and Use of Visual Information.. 3-54
B. The Relation Between Individual Differences and the Intake and Use of Visual Information...... 3-57
C. Problem Solving................................ 3-59

CHAPTER 4. Instrumentation and Instrumentalities........... 4-1

I. Research Management, Review and Support........... 4-3
II. Instrumentation Development...................... 4-6
III. Facilities Dissemination and Establishment........ 4-9
A. Instruments of Moderate Accuracy and Resolution 4-9
B. Instruments of High Accuracy and Resolution, and of Intermediate Cost..................... 4-11

CONTENTS (Cont.) | Page

C. Central Facilities For Expensive Equipment and Services	4-12
IV. Priorities	4-16
REFERENCES	Ref. 1
APPENDIX	
Survey of Eye-Movement Recording Methods	App. 1

PREFACE

From June 10 through June 21, 1974, the National Institute of Education sponsored a two-part conference on eye-movement research and technology in Columbia, Maryland. The purpose of the first part of the conference was to survey the current knowledge in the field of eye-movement research about visual information processing in general and reading in particular, and to suggest profitable directions for future research addressed to both theoretical and applied issues. The purpose of the second part of the conference was to assess the current state of the technology for eye-movement research, to offer suggestions for improvements in eye-movement instrumentation, and to explore possibilities for more efficient data analysis procedures.

The core group for both parts of the conference consisted of:

Mary Carol Day, Harvard University
Edward DeAvila, Bilingual Children's Television
Barbara N. Flagg, Harvard University
Samuel Y. Gibbon, Jr., Children's Television Workshop
John J. Geyer, Rutgers University
Marshall M. Haith, University of Denver
Julian Hochberg, Columbia University
Kenneth G. O'Bryan, The Ontario Institute for Studies in Education
Juan Pascual-Leone, York University
David Sheena, Whittaker Corporation
Sheldon H. White, Harvard University

Various representatives of the Essential Skills Program of NIE participated from time to time during the conference. They included Elizabeth Daoust, Donald Fisher, Monte Penney, Marshall S. Smith, Nancy Yanofsky, Ron Leslie, Timothy Hodapp, and William Ashcroft.

The conference was administered by Nero and Associates of Portland, Oregon, under a contract with NIE. David Judd of Nero had principal administrative responsibility. Carol Kolson assumed day to day administrative duties during the planning of the conference and during the conference itself, and was in charge of all logistical arrangements.

The conference commissioned Laurence R. Young of M.I.T. and David Sheena of Whittaker Corporation to write a paper reviewing the state of the technology for eye-movement research to serve as a basis for discussion during the part of the conference concerned with instrumentation. This most useful document is appended to the report.

A total of 31 consultants contributed their ideas and recommendations to the conference -- 24 for the research sessions and 7 for the

instrumentation discussion. Most of the research consultants submitted briefing papers to the core group. Fourteen of the research consultants also attended the conference for a day each to discuss their and other suggestions with the core group.

The list of contributing consultants follows:

Research Consultants

*Dr. John S. Barlow
Massachusetts General Hospital

*Dr. Patricia A. Carpenter
Carnegie-Mellon University

Ms. Karen M. Cohen
University of Denver

*Dr. Roger N. Cooper
Stanford Research Institute

*Dr. Dennis F. Fisher
U. S. Army Human Engineering Laboratory

*Dr. Lila Gleitman
University of Pennsylvania

*Dr. John T. Guthrie
John Kennedy Institute for the Habilitation of the Mentally and Physically Handicapped

*Dr. Ralph N. Haber
University of Rochester

Dr. Paul A. Kolers
University of Toronto

*Dr. Jane Mackworth

*Dr. Norman H. Mackworth
Stanford University

*Dr. George McConkie
Cornell University

Dr. Frank J. McGuigan
Hollins College

Dr. Ulric Neisser
Center for Advanced Study in Behavioral Sciences

Dr. Jum Nunnally
Vanderbilt University

Dr. David Otto
Environmental Protection Agency

Dr. S. Jay Samuels
University of Minnesota

Dr. Judah Schwartz
Massachusetts Institute of Technology

Dr. Lawrence Stark
University of California

*Dr. Richard L. Venezky
University of Wisconsin

*Dr. Stanley F. Wanat
University of California

Dr. William Wang
University of California

*Ms. Muriel Thompson Watkins
Harvard University

Mr. Thomas Wolf
Harvard University

Instrumentation Consultants

*Dr. Hewett Crane
Stanford Research Institute

*Dr. Derek H. Fender
California Institute of Technology

*Mr. Henry R. Jex
Systems Technology Inc.

*Dr. Alan Kay
Xerox Palo Alto Research Center

*Mr. Robert H. Lambert
U. S. Army Human Engineering Laboratory

*Dr. Richard A. Monty
U. S. Army Human Engineering Laboratory

*Dr. Laurence R. Young
Massachusetts Institute of Technology

Draft sections of this report were written by members of the core group, working together at the conference and separately after the conference ended. Their writings have been edited, but the conclusions reached and the recommendations offered are those of the entire group.

*These consultants attended the conference sessions held in Columbia, Maryland.

FOREWORD

In the summer of 1972 a group of distinguished scientists convened at Hyannis, Massachusetts, to design a program of research on reading and the related language processes. The report of the Hyannis meeting,[1] provided impetus for NIE's decision to declare a major priority on reading.

During 1973 and 1974 NIE organized a series of meetings designed to plan in greater detail some of the research initiatives suggested by the Hyannis group. Emphasis was placed upon finding ways to identify research that could be helpful in explaining the cognitive processes that enable people to comprehend what they read. The meeting on Visual Information Processing (VIP), reported in the following pages, was conducted in the belief that research on eye movements and the cognitive processes they serve will continue to be a source of valuable insights into the nature of reading comprehension.

Special thanks go to Samuel Y. Gibbon, Jr. for his leadership in creating and conducting the planning project on visual information processing. He performed the duties of chairperson with energy and with attention to insuring that all points of view received fair and thorough treatment. He was ably assisted by Mary Carol Day, by Barbara Flagg, and by Nero and Associates, the firm that carried out the organizational arrangements for the meetings.

On behalf of the Institute, we also gratefully acknowledge the work of the participants in the Conference and all of the research consultants who prepared briefing papers or presentations.

Perhaps the most appropriate expression of thanks NIE can make to the many persons who have offered advice on visual information processing is to take their advice seriously. Those of us who have been working to formulate a strong NIE program of research on reading and related issues have come to believe that as long as reading remains a priority of the Institute, there should be an annual grants competition for basic research that seeks to build scientifically adequate theories about reading comprehension. We expect that workers in visual

[1]Miller, George A. (ed.) Linguistic Communication: Perspectives for Research. Newark, Delaware: International Reading Association, 1974, 45 pp.

information processing, because of their long history of productivity, will be prominently represented among the advisers, reviewers, and grantees of such a competition.

Monte Penney
Marshall S. Smith
Learning Division
Basic Skills Group
National Institute of Education

CHAPTER 1

INTRODUCTION AND GENERAL RECOMMENDATIONS FOR EYE-MOVEMENT RESEARCH AND INSTRUMENTATION

Vision is the dominant sense in humans. The areas of the brain devoted to the acquisition and processing of visual information are larger than the areas concerned with information from any other of the senses. The retina of the eye, unlike any other sensory receptor, is composed of brain tissue; it is a part of the central nervous system. The eye enjoys a favored role as principal sensory advisor to the brain.

Not unreasonably, then, communication between humans makes frequent and heavy use of the visual channel. As human society has advanced, the quantity, complexity, and importance of visual messages have increased geometrically. Skill in reading printed language and skill in "reading" still and moving pictures have become requisites for social survival.

Remarkably little is known about how visual information is received, processed, stored and retrieved. What is known about the structure and functioning of the human eye suggests that despite its importance, it is a curiously limited receptor of visual information. Only a tiny, roughly central area of the retina called the fovea is capable of resolving images with a high degree of acuity. The surrounding retinal periphery falls off sharply in acuity with increasing distance outward. Yet this narrowly tunneled receptor is the principal supplier of sensory information to the brain.

In order for the brain to receive detailed information about the visual environment, the eyes must be made to jump about the field of view so that successive images of small portions of the environment may fall upon the fovea. The jumps, called saccades, are exceedingly rapid. The pauses for foveation of the image, called fixations, are brief. Somehow, marvelously, from these small samplings of the visually available environment there is constructed and maintained in the mind a stable image, rich in meaning, of the external world.

If the image-receptive powers of the eye are limited, the richness of visual information must result from the analyses and integrations performed by the brain on the miserly parcels of data delivered to it by the eye. Furthermore, the brain must direct the eye to sample the environment with maximal economy for maximal information; successive fixations must provide the brain with the information it requires from moment to moment. The brain tells the eye where to look and what to

look for. Direct observation of the operation of the human brain is possible only in conditions of pathological extremity where surgical intervention is required. Even then the neural explorations of the scientist reveal little of the hidden recesses of thought. Because of the intimate real-time connection between the behavior of the looking eye and the higher cognitive processes which both guide that behavior and are in turn informed by it, observation of the movements of the eye permits powerful inferences to be drawn about the workings of the mind.

Reading printed messages is among the most complex of human activities, involving the extraction of language from graphic symbols and the extraction of meaning from language. "Reading" still and moving pictures organized for communication is perhaps as complex and certainly less diligently investigated. The behavior of the eye in response to visual messages merits fine and devoted observation.

In this chapter we offer three general recommendations and discussions to support them. Section I recommends that NIE support eye-movement research on the acquisition and processing of information from the visual media of printed text, pictures and other static graphic displays and television. Section II suggests that such research will be maximally useful if it is guided and organized by theoretical conceptions and recommends that NIE support the development of such conceptions. Section III argues the need for adequate instrumentation in order to collect the accurate data which can confirm or refine theory; NIE is urged to support the dissemination of improved technology.

Subsequent chapters propose more specific recommendations deriving from and elaborating upon these general recommendations. The recommendations in chapter 3 relate explicitly to the general recommendation offered in section I and, implicitly, to the general recommendation in section II. Chapter 4 sets forth detailed suggestions for the types of instrumentation needed to fulfill the recommendation in section III and suggests ways of managing its dissemination and use.

I. RESEARCH

RECOMMENDATION: The NIE should establish and maintain support of research directed toward the study of eye-movements, scanning, orienting-investigatory behavior and visual information-processing. Such research should be addressed particularly to exploring the acquisition and processing of information from the visual media of printed text, pictures and other static displays, and television.

Consultants coming before the conference, and the considerable body of research work reviewed by the panel, all tended to suggest that there is at present a significant growth of research on visual scanning and search processes. This work proceeds forward under a variety of labels (e.g., eye-movements, scanning, vigilance, search patterns, orienting behavior, orienting-investigatory behavior, attention, etc.). There are distinct, somewhat segmented zones of research work. No one theoretical conception guides the work but, rather, a variety of theories or models exist. Nevertheless, the growth of this body of work is deeply tied to theoretical considerations. The trend of contemporary theorizing in psychology and the neurosciences makes this kind of work desirable and inevitable.

The important trend in analytic work today is toward what one might call a "developmental" or "dynamic" or "real-time" analysis of cognition. Until quite recently, theorizing about learning, motivation, or human ability was always cast in terms of static or timeless elements -- as, for example, the numerous trait models of human intellect or personality. The present trend is toward systems that portray perception and cognition as a matter of assembly or construction of meaning over real time. In such systems, individual differences emerge as cognitive "controls" or "styles," the differences reflected in the models as heterogeneous biases in assembly or constructional processes.

This kind of analysis of the temporally integrative processes in cognition is now manifest on two time-scales, both of some significant interest to the NIE. One might see these two time-scales related as physics is to geology.

One sector, the "physics" of the study of cognitive construction, is that body of work that is now conventionally referred to as the study of information-processing. It is an analysis of the organization of perception and it involves study and inference about events on a time scale ranging from microseconds to tens of seconds. This kind of analysis seems important for further examination of the tactics of education. It allows one to study in some detail the real-time processes that maintain or disrupt the child's engagement with ongoing

classroom processes. It is at this level of analysis that one may seek to find optimizations of techniques, media, and teacher approaches to children.

The other sector, the "geology" of the study of cognitive construction, is that body of work that is now conventionally referred to as the study of cognitive development, in particular the kinds of analysis associated with Piaget, Werner, and Bowlby. This is an analysis of the organization of meaning-systems and affect-systems in children over a time scale of months and years. This kind of analysis seems important for further examination of the strategies of education. The strategies of education cannot be developed solely through the elaboration of an analysis of the child and his development, because what education does rests as much upon societal considerations as it does upon considerations of cognitive development per se. But it seems abundantly reasonable that the efficacies and inefficacies of education in conducting its social mission depend upon present unknowns with respect to the processes and possibilities of cognitive development in children.

The work of these two sectors, the "physics" of information-processing and the "geology" of cognitive development, has led to a significant convergence. Many influential contemporary theories regard scanning or search patterns as a kind of kernel of stored meaning. As one identifies unique objects and relations in experience by means of unique action systems, it is the stored programs for such action that constitute the basis for memory or knowledge. Recent technological developments have made possible the elaboration of this theoretical position. At the information-processing level, the work of Liberman and the Haskins Laboratory group favors this kind of interpretation of auditory recognition; the work of Neisser and Sperling argues for it in visual recognition. At the level of cognitive development, the work of both the Russians (Zaporozhets, Leontiev, Luria) and of Piaget has tended more and more to recognize the child's actions and action systems as the basis for his construction of reality.

These theoretical developments have tended to give research on scanning, on forms of active encounter with experience, a more and more central place in current research on cognition. It seems important now to transpose educational analysis and educational thinking toward such a research basis. Indeed, one can argue that most of the more significant new writing about the processes of education seems significant precisely because it begins this transposition.

Seeing has traditionally been separated from acting, and knowing from acting. At the heart of current theory is the understanding that seeing is a form of acting. The most conspicuous of the acts of seeing are the movements and fixations of the eyes by which we successively bring into regard and attention selected pieces of the world. Through analysis and integration of these successive brief and narrow views we

construct pictures and patterns of reality. Especially is this true in encounters with visual messages. It is one thing to scan a picture; it is another to read a paragraph of text. Yet, in both cases a complex time sequence of actions is fundamental to understanding -- to knowing -- what is given. Eye-behavior is among the most highly observable components of the temporal construction of meaning.

Central to the issue of reading is the problem of knowing. To comprehend text is to come to know through reading. Recent research has explored in more and more sophisticated ways the complex relation between sequences of eye-movements and vicissitudes and quirks in the reader's understanding of logical, grammatical and conceptual relationships offered to him in text. It has become abundantly clear that if we want to know more about comprehending, we must know more about the successive acts with which the construction of comprehension begins and by means of which it proceeds; and we must observe sustained sequences of those acts as they are performed on extended passages to be comprehended. No other existing technique compares with eye-movement study as a direct, efficient, clear means by which we can observe the nature, order and duration of those acts as they are performed.

There is good reason to believe that there are age differences in eye-movement patterns. There is good reason to believe that there are individual differences, originating in both the style and the intellectual structure of the reader. We must, then, be prepared to make increasingly close-grained and far-reaching studies of the eye-movements of readers in order to clarify the knowns and penetrate the unknowns of reading comprehension.

The importance of reading in schools lies in the fact that text has been the predominant device by which men's minds are brought into convergence on facts and ideas. Our complex social system is built on shared thought. That is why our system depends upon schools. Taking a larger view, and one that is not futuristic, we must now recognize that our society increasingly shares facts and ideas through pictures and television. In ways different from text, these media advance sharing and cooperation in thought in our society. The NIE's responsibility is not simply to reading, but to the issue which reading represents, which is the construction of an _e pluribus unum_ of thought. We face the same issue with the new media: eye-movements bound into temporally organized succession, age differences, individual differences, all registered in dynamic configurations of acts of seeing. Eye-movement research is no less vital to understanding this kind of comprehension; and it is in the interest of NIE to advance all these forms of comprehension through the advancement of scientific acts by which science may see and know them.

II. THEORY

RECOMMENDATION: The NIE should encourage and support attempts to set forth theories, models, or simulations of information-processing as it occurs in responses to text, pictures and television.

A theme reiterated repeatedly by those coming before the conference was the need for good theories of skilled reading. There was wide general agreement that there exists today no complete, coherent and exhaustive theoretical understanding of how people read, this despite some genuinely hopeful beginning made during the past decade. Until such theoretical work advances to a level of predictive adequacy, research will continue to be fragmented and beset with hidden definitional difficulties; and instructional practice will continue to be limited to the stumbling trial and error methods of the past.

The reading process had been a major subject for research in American and European psychology during the period prior to World War I. With the rise of Behaviorism, however, the mainstream of American psychology was diverted from the study of cognition to learning, from human to animal experimentation, and from purposive to mechanistic explanation. Until the very recent past, and to a considerable extent today, the ideas which guide much programmatic research and development in reading, and which underlie the teaching methods of hundreds of thousands of classroom teachers include conceptualizations of the reading process which are the product of Victorian scientific study in a field then in its infancy. It is a measure of the inadequate development of reading theory that Huey's 1908 work on the psychology of reading is far from outdated.

During the past decade there has been a resurgence of interest in theoretical questions about cognition. Present theoretization is notably stronger than that which preceded it. The formal models of mathematical learning theory are more precisely formulated and more rigorous in prediction, the informal models of Neisser and Piaget more intuitively plausible and more general in their implications. Computer simulation and artificial intelligence have emerged as a kind of breakthrough in model-building; the technology both permits and demands more careful and elaborate theoretical analysis than has ever before been possible. Finally, the development of the neurosciences has progressed to the point where they are helpfully prescriptive to the psychologist; and the earlier view that psychology and physiology had little to say to each other is clearly untenable today.

As cognitive theory in general has strengthened and become more interdisciplinary, interest in theoretical questions about the cognitive processes in reading has reawakened. In part this reawakened interest

has been forced upon the field by an explosion of information bearing upon the reading act which has occurred in a number of diverse fields, and which can no longer be contained within the bounds of tight specializations. The very extent of overlap found among previously discrete areas of study has required integrations at finer levels of detail and higher levels of abstraction; for the commonalities discovered have been not merely in the problems studied but in the general principles governing phenomena. For example, a mutual interest in how patterns are recognized has brought together scholars from such diverse fields as neurophysiology, psychology, computer science, and engineering to produce work with clear relevance to an understanding of some aspects of reading.

Theoretical work ought also to be encouraged toward understanding how people look at and process information from pictures and other static graphic displays of varying degrees of abstractness.

Most notable by its absence is an articulated theory of any kind about the acquisition and processing of information from television. Carpenter and McLuhan have not been taken as seriously as they should have been, but it remains for their notions to be expressed in language that makes them accessible to perceptual and cognitive scientists. And there is surely ample room for other theoretical positions to be taken. Any theories, even nascent partial theoretical thinking, about how information is processed from television would have relevance for the use of the medium for instructional purposes, and could contibute immediately and substantially to the improvement of such applications.

There is a kind of cultural or diffusional lag between psychology and education. Too little of the current theoretical activities of cognitive psychology have yet been carried into educational research and practice. Sooner or later, of course, the diffusion will take place but it is in the interest of education that it be strengthened and facilitated. The NIE could and should play a leading role in this process by encouraging theoretical work and its responsible application to practice. As a first essential we must know more about the cognitive processes involved in skilled reading and other visual information-processing tasks. Secondly, we must know how these processes develop and how this development is influenced by social, cultural, and educational factors. These are massive questions calling for careful long-term research and development. The experience of the past decade suggests, however, that they are feasible goals. While final answers may require decades of work, the payoff in terms of viable practical ideas would accrue incrementally and has already been significant. At any rate, this type of theoretical work is our best hope for sources of ideas for genuine, significant educational change and should be fully encouraged.

III. INSTRUMENTATION

RECOMMENDATION: The NIE should encourage and support the dissemination of technology for eye-movement research, for computerized data analysis and for theoretical work. The NIE should support the dissemination of related technologies: tachistoscopes, psychophysiological instrumentation, auditory signal-processing technology, and computer animation and experimental television. The NIE should support the further development of these technologies.

Not all the reasons for research work and research traditions are noble, theoretical, or ideological. There is an inexorable practicality about research work that is so obvious that it is usually dismissed or ignored in programmatic writings. One works with what one has or with what one can quickly get. If one chooses to work in a problem-centered way, choosing methods to fit problems rather than problems to fit methods, one still finds important constraints related to methods.

This seems well illustrated by the history of eye-movement studies in the U.S. The potential significance of eye-movement research was recognized early in this country. A significant body of research was collected. The work was of considerable interest, but it never proliferated and became widely established -- as did, for example, work with the memory drum, paper and pencil testing, or various kinds of experimental studies of learning. One might suggest that this kind of growth pattern in research was fixed in part by shortages of technology and in part by the undercapitalization of laboratories devoted to psychological and educational inquiry.

One of the reasons why there seems now to be a resurgence of work on eye-movements is probably the gradual solution of these practical obstacles. Research on eye-movements has been made significantly easier by newer instrumentation and by the introduction of capabilities for on-line data processing. The development of this newer instrumentation has been made possible in part by technological development, the emergence of smaller and cheaper computers, but also by the willingness of sponsors of eye-movement research to underwrite the development of instrumentation.

Many of those who came to address this conference came from active work on eye-movements in laboratories that, from the perspective of psychology and education, could fairly be regarded as high-technology centers. To some extent the lead-lag relationship between their work and the great body of the "normal science" that surrounds it is fixed by the availability of technology.

There is today a growing aversion to method-centered research and method-centered thinking about research. There is, as well, some suspicion of gadgetry as a kind of diversionary hobby within the research community. In its earliest announcement of support for basic research, for example, the NIE specifically disavowed any willingness to fund the development of instrumentation. However, there may be a baby in the bathwater. By explicitly discouraging methods-centered research, one can implicitly encourage a kind of negative form of the problem.

It seems likely today that the general body of research on information-processing, reading, signal-processing, and cognition would be aided in important respects by the wider availability of more precise and more powerful instrumentation. The yield would be more precise research, more ambitious programs of real-time data collection, and increased capabilities for computerized data-processing. Linkages could be sought between scanning, cognitive analysis, and psychophysiology.

This kind of technological development would not solve all the problems of reading or educational research, by any means, and it would undoubtedly introduce a good number of predictable problems. Set against it, one has counterexamples -- e.g., Piaget or Lorenz -- where large scientific advances have been built upon barehanded research methods. Nevertheless, a significant trend in American research work -- the trend of Sperry, Simon, Liberman, Neisser, Posner, etc. -- rests upon technological refinements and it seems likely that that trend cannot be formative for educational research unless significant provision can be provided for a counterpart technological base within educational research.

CHAPTER 2

SUMMARY OF SPECIFIC RECOMMENDATIONS

Chapter 1 presents general recommendations to the effect that NIE should foster research, theory-building, and improved instrumentation in the field of visual information processing. The more specific recommendations of the VIP planning group are presented in four clusters below. A page number reference appears at the end of each recommendation to aid in locating the relevant discussion in the report.

A. READING TEXTS, PICTURES, AND OTHER GRAPHIC DISPLAYS

RECOMMENDATION: The NIE should support the exploration of moment-to-moment information intake and processing mechanisms involved in the encounter of the child or adult with text, pictures and graphic displays. This is a research priority for which eye-movement technology is a *sine qua non*. The general needs are: (1) to record time sequences of moves (saccades) and stops (fixations) of the eyes as well as the point of fixation during stops as the subject confronts visual material; and (2) subsequently to relate this pattern of scanning to (a) theoretical conceptions about the operation and development of assimilatory mechanisms; and (b) to short-term memory and/or processing, and the elaboration of knowledge. (p. 3-3)

More specifically, the NIE should:

(1) Support research exploring the size of the perceptual span during a fixation as a function of the skill and developmental levels of the reader, the characteristics of the text, and the levels of certainty required by the task. (p. 3-4)

(2) Support investigation of the allocation of attention within the stationary field of fixation and the temporal distribution of information intake during fixation. (p. 3-7)

(3) Support research on the peripheral visual and cognitive controls over the timing and extent of a saccade. What guides and directs an individual's eye-movements? (p. 3-10)

(4) Support research that tests the generality and boundary conditions of the proposition that where the eye looks at any moment reflects the item of information that is of particular importance in cognitive processing at that moment. (p. 3-13)

(5) Support research which examines the orchestration of saccades as a function of the goal and state of the reader. (p. 3-15)

(6) Support research which explores the nature, duration and sequence of the component processes involved in reading and the integration of these component processes. (p. 3-17)

(7) Support research which explores the encoding and construction of the message as a function of the knowledge system of the reader and the linguistic and semantic characteristics of the text. (p. 3-20)

(8) Not support the wide-scale use of eye-movement data as a diagnostic indicator of reading deficiency given our current knowledge base. (p. 3-22)

(9) Support studies which examine the factors in text which facilitate the initiation, maintenance and direction of active looking and facilitate learning or message retrieval. (p. 3-23)

(10) Support research which explores the effect of age on the acquisition and use of visual information presented in pictures and graphic displays. (p. 3-26)

(11) Support research exploring the optimal use of illustrations and text in combination. (p. 3-28)

(12) Support research directed towards the assessment of verbal comprehension. (p. 3-29)

B. PROCESSING TELEVISION DISPLAYS

RECOMMENDATION: The NIE should support the exploration of moment-to-moment information intake and processing mechanisms involved in the encounter of the child or adult with television. This is a research priority of highest order, for which eye-movement technology is a sine qua non. The general needs are: (1) to record the sequential behavior of the eyes (saccades, fixations and smooth pursuit) as well as the point of regard of the subjects' eyes on the televised display; and (2) subsequently to relate this pattern of eye behavior (a) to moment-to-moment analyses of the dynamic

stimulus and (b) to theoretical conceptions about the operation and development of assimilitory mechanisms, short-term memory and/or processing, and the elaboration of knowledge. (p. 3-31)

More specifically, the NIE should:

(1) Support the articulation of theoretical analyses of the elements of the television code and the structural rules by which those elements are temporally and spatially combined, and research to test and refine these analyses. (p. 3-33)

(2) Support eye-movement research that explores the moment by moment relations between the special structural properties of television and the perceptual, cognitive and affective processes of the viewer. Such research should consider these relations as a function of the age, knowledge, skill, purposes and cognitive style of the viewer. NIE should be prepared to support, as a part of this research, small-scale experimental production of television and film material and the design and production of computer animation that allows on-line modification of the stimulus while the viewer is watching it. (p. 3-37)

(3) Support research that explores the limits of television's intrinsic power to instruct, to model cognitive processes and to aid in the construction of mental representations. Such research should examine the instructional effects with respect to the characteristics of viewers. Small-scale experimental production should be supported. NIE should encourage research that relates to and advances theories of instructional television. (p. 3-41)

(4) Support research that explores the limits of television's power to teach and to motivate reading. Small-scale experimental production should be supported. (p. 3-45)

(5) Support research that (1) investigates the moment-to-moment intake and processing of information from television by very young children, adult illiterates and speakers of language and dialects other than standard English, and (2) explores other potential informational and instructional uses of the medium to inform and teach these populations. (p. 3-48)

C. OTHER APPLICATIONS OF EYE-MOVEMENT RESEARCH

RECOMMENDATION: The NIE should support research which employs eye-movement recording to explore psychological states and processes not limited to those involved in reading,

picture scanning, and television viewing. This recommendation is based upon the assumption that knowledge relevant to such specialized processes as those involved in reading can eventuate from research which addresses more general issues in cognitive and psycho-motor development.

More specifically the NIE should:

(1) Support developmental studies which chart the capability of the visual control systems of children of different ages. (p. 3-54)

(2) Support research which explores the relation between cognitive development and the intake and use of visual information. (p. 3-56)

(3) Support studies of individual differences in the intake and use of visual information that may relate to educability. (p.3-57)

(4) Support eye-movement research which explores steps in problem solving and variations in those steps as a function of individual or group differences (e.g., age, cognitive style). (p. 3-59)

D. INSTRUMENTATION AND INSTRUMENTALITIES

RECOMMENDATION: The NIE should develop its own capacity and that of the field to stimulate research in visual information processing.

More specifically the NIE should:

(1) Establish a study panel to: (1) encourage and evaluate field-initiated research that uses eye-movement (or simulated eye-movements) to study and assess essential skills in reading and comprehension, picture scanning, and television viewing; (2) assign and periodically revise research priorities in the area; and (3) supervise the development and dissemination of needed instrumentation. (p. 4-3)

(2) Invite and support, the study panel should oversee, replications of existing studies to determine the extent to which the eye-movement behaviors observed in the original studies are specific to the particular laboratory setting and not representative of normal behavior. (p. 4-4)

(3) Invite and support specific research and development of instrumentation to improve the ease, efficiency and validity of eye-movement research. This research and development should be addressed both to the development of new instruments and to the improvement of existing instruments. (p. 4-6)

(4) Support, and the study panel should oversee, the dissemination of eye-movement instruments and related technology, and the establishment of facilities which increase the ease, accessibility and efficiency of eye-movement research on reading, the scanning of pictures and graphic displays and television viewing. (p. 4-9)

CHAPTER 3

SPECIFIC RECOMMENDATIONS FOR DIRECTIONS IN EYE-MOVEMENT RESEARCH

The recommendations for research set forth below derive from and expand upon the first general recommendation made in Chapter 1: that the NIE should establish and maintain a program of research in eye-movements and visual information processing. Beyond the merits of the suggested topics for research, it is hoped that this chapter will be persuasive of two general points: first, that eye-movement research can be of unique value in testing and refining theories and models of reading and visual information processing; and second, that the data acquired in empirical studies such as those proposed below will encourage, indeed perhaps require, the development of new theoretical models.

The research recommendations that follow should not be regarded as exhaustive, or preemptive of field-initiated proposals for research which have not been recommended here. Rather, these recommendations should be taken as illustrative of the important substantive questions that can be addressed using eye-movement technology. As better theories and models of reading and visual information processing are developed, better research questions will be asked; and NIE's program of eye-movement research should remain flexible enough to meet the changing needs of the field.

This chapter is divided into three main sections. Section I recommends eye-movement research that explores the moment-to-moment information intake and processing mechanisms involved in the encounter of the child or adult with text, pictures, and other static graphic displays. Section II suggests research that explores the intake and processing of dynamic visual information as it is received from television. Section III argues the general value of eye-movement research, using a variety of static and dynamic stimuli, for the investigation of such psychological issues as cognitive development, individual differences, and the development of problem solving strategies. In all three sections it will be seen that the research recommended ranges from basic inquiry about human systems of perception and cognition to studies applied to the improvement of instructional materials.

The acquisition and processing of information from visual material organized for communication is a complex purposeful activity, pursued for reasons that are as complex and subtle as those that occasion any

real-life activity, and conditioned by all the rich differences that we expect to find between individuals, age groups, and cultures. However, there are certain characteristics of the visuomotor system which are common across individuals.[1]

The eyes of the alert person are in constant motion. During reading and during the viewing of other static displays, the eyes move in fast jumps called saccades. The stopping periods between the moves are called fixations. In reading and in saccadic viewing generally, well over ninety percent of the time is spent with the eyes fixated. Since little or no useful vision occurs while the eyes are in saccadic motion, almost all visual information is extracted during fixations.

As a person views a picture or reads along a line of print from left to right and down the page, his eyes jump from position to position stopping or fixating at each position from one-tenth of a second to a full second, with an average fixation duration of 250 msec. During a fixation, some information in the center of the field of view will be seen clearly, while surrounding material will be less clear. The visual area in clear focus is imaged on the fovea, a small central area of the retina which can resolve fine detail. The fovea subtends a visual angle of approximately 1° (Adler, 1965). Visual acuity drops off rapidly and continuously in the area outside the fovea, the peripheral retina or periphery.[2] The drop-off rate in visual acuity for adults is under debate (Kerr, 1971); recent results indicate that peripheral acuity has been underestimated and that an individual is more sensitive to peripheral input than had been previously thought. It is somewhat remarkable to note, however, that no reliable data exist on developmental changes in peripheral acuity; this information is crucial to consideration of the beginning reader or young viewer (see section III, below).

Traditionally, research on vision has emphasized the importance for visual information processing of the structural difference between the fovea and the periphery. Recently, however, some researchers have emphasized a complementary consideration of the visual field invoking attentional factors (i.e., focal attention, centration) as also playing a major role in visual information processing. (Research based on each of these perspectives will be considered in section I. A. 1.)

---

[1]A more detailed discussion of the movements of the eye can be found in the Appendix, Survey of Eye Movement Recording Methods.

[2]It must be noted that a not-well-defined midstage between the foveal and peripheral retinal regions has been proposed, the parafovea; however, for simplicity, this report will restrict its terminology to foveal and peripheral vision.

I. READING TEXTS, PICTURES, AND GRAPHIC DISPLAYS

RECOMMENDATION: The NIE should support the exploration of moment-to-moment information intake and processing mechanisms involved in the encounter of the child or adult with text, pictures, and graphic displays. This is a research priority for which eye-movement technology is a *sine qua non*. The general needs are: (1) to record time sequences of moves (saccades) and stops (fixations) of the eyes as well as the point of fixation during stops as the subject confronts visual material; and (2) subsequently to relate this pattern of scanning to (a) theoretical conceptions about the operation and development of assimilatory mechanisms; and (b) to short-term memory and/or processing, and the elaboration of knowledge.

Eye-movement behavior is a directly observable, real-time, continuous variable which allows moment-to-moment estimations of the acquisition of visual information. Moreover, as argued above in Chapter 1, the pattern of stops and moves of the eyes reflects cognitive processes. Eye-movement recording, however, is not the usual method chosen from the variety of experimental techniques and instrumentation available to the researcher interested in visual information processing. Generally, the techniques used are designed to eliminate the effects of multiple fixations through tachistoscopic or fixed retinal image procedures. The results of this experimentation, while often precise, are difficult to extend to the normal, on-going visual processes of reading or picture scanning. Recently developed equipment which combines tachistoscopic and eye-movement monitoring capabilities (cf. McConkie and Rayner, 1973a, 1973b) provides a sophisticated instrumental base for understanding the processes underlying the orchestration of stops and moves of the eyes.

In this section, eye-movement behavior in response to text is considered separately from scanning of pictures and other graphic displays. Although the processing of both text and pictures draws on the same visuomotor systems and both cases involve purposeful behavior toward static stimuli, the nature of the stimuli and tasks are such that separate consideration is desirable. The reading task introduces a linguistic component not present in the visual scanning of pictures and also requires that eye-movements accommodate to a particular spatial arrangement of the stimulus (e.g., left-right, top-bottom). The more extensive discussion of eye-movement research in reading in part reflects the heavier emphasis given that topic during the conference.

Moreover, except where clearly inappropriate, the specific recommendations made in the text section concerning moment-to-moment information intake and processing apply similarly to pictorial material.

A. TEXT

The following section divides the discussion of eye-movement behavior in response to text into three parts: section 1, Considering Stops, suggests the need for research on the amount and type of information a reader may acquire during a single fixation on a line of text; section 2, Considering Moves examines the factors which may influence the timing and targeting of saccadic movement of the eyes within textual material; section 3, Considering the Orchestration of Stops and Moves, explores the purposeful application of the visual system to the retrieval of meaning from extended text.

1. Considering Stops

RECOMMENDATION: The NIE should support research exploring the size of the perceptual span during a fixation as a function of the skill and developmental levels of the reader, the characteristics of the text, and the levels of certainty required by the task.

Despite the fact that the retina subtends a rather large visual angle, when a viewer fixates on a display he does not process all the information available within that angle. Very little is known about the size of the area from which a reader obtains visual information during a fixation; that is, little is known about a reader's perceptual span. It is thought that this perceptual span is not static but may vary in size as a function of different factors such as reading skill, text characteristics, and levels of certainty required by the task, but there is limited empirical information related to this matter. In addition, little is known about what type of information an individual acquires within his perceptual span.

Recent research (McConkie and Rayner, 1973a, 1973b; Rayner, 1974) indicates that the skilled reader uses different classes of information at various locations within the perceptual span. Rayner (1974) reports that a skilled reader can make semantic interpretations for words within 1-6 character spaces of his fixation point (1-2° of visual angle). Furthermore, general word shape and the initial and final letters of a word may be detected up to 12-18 character spaces from the reader's fixation point (3-5° of visual angle). McConkie and

Rayner (1973a) found also that word length information was available to the reader inside 12-15 characters from the fixation point. Thus, there appear to be several levels of recognition available within the same fixation.

This pioneering research was conducted with innovative instrumentation which allows alteration of the text as a function of the subject's eye-movements. A printed passage is displayed on a cathode-ray tube; as the subject reads the passage, an on-line computer is used to alter the text available to his peripheral vision. Thus, in each fixation a small "window" of unaltered text is presented to the fovea, but the text presented to the periphery of the retina is systematically altered. A great number of previously unanswerable questions about perceptual span can now be considered with this new technology.

Perceptual Span as a Function of Skill and Developmental Levels of the Reader

An important research question to consider is whether the size of the perceptual span is in part a function of the unit of recognition the reader uses. This "unit" is ill-defined at present but essentially refers to the level of detail at which the reader is sampling the text during the reading act. Presumably, the "unit" increases with increased reading skill. For the beginning reader, the typical unit of recognition is probably a set of distinctive features or the letter. As he learns to read, all of the beginning reader's attention and processing capacity may be addressed first to identifying letters; gradually, with practice, letter recognition becomes automatic and a higher-order unit code may be used -- spelling patterns, words, word groups. The skilled reader often recognizes words of many letters in a single fixation (with no eye movements being performed to bring different letters to the center of the fovea).

Does the ability to pick up information in the visual periphery change as a function of one's level of reading skill? Does the automatization or elimination of smaller unit processing (i.e., features, letters) or the usage of higher-order unit codes (i.e., spelling patterns, words) increase the perceptual span from which the reader can make semantic interpretations? Does the time and attention expended by the unskilled reader in processing foveated "units" restrict the perceptual span and preclude peripheral pickup of grosser text characteristics? Does the speed reader utilize an expanded perceptual span or is he simply better at constructing meaning from fewer bits of information? Basic research is necessary on changes in the size of the perceptual span and what information is available and used from the periphery as a function of increasing reading skill.

In the above discussion of the perceptual span in relation to skill of a reader, it was assumed that a beginning reader could be an adult as well as a child. If we consider children in particular, there are

several ways in which developmental changes might affect the size of the perceptual span and the use of information within the span (see also section III, A). Possible research questions include the following: Does peripheral acuity develop with age? If so, how does this development affect the child's perceptual span in reading? Does the span vary with developmental changes in linguistic knowledge? Does limited attentional capacity or "processing space" restrict the number of information "units" the child can process within one fixation (Pascual-Leone, 1970)? Does the attention or space required for handling foveated stimuli limit the child's ability to pick up peripheral information?

Perceptual Span as a Function of the Characteristics of the Text

On occasion the skilled reader will meet words he has never seen before and may be required to fixate on individual letters or letter combinations as a beginning reader does. When the reader comes to words that he does not recognize, multiple fixations are made among the internal letters; we do not know how these eye-movements aid the recognition process, but they do serve as an indication of the difficulty of the text for an individual reader. The point to be made here is that during continuous reading even the skilled reader processes text at varying levels of analysis and with different unit codes.

Thus, the perceptual span is not dependent upon reading skill alone but probably varies also in the skilled reader with difficulty of the material to be read. Research using computer-controlled CRT displays might consider the influence of various text characteristics on the perceptual span. For example, do grammatical constraints, the predictability or redundancy of the text, and the complexity or density of text (i.e., lexical, linguistic, logical) affect the span? How does print size and/or word or "unit" spacing affect the perceptual span?

Perceptual Span as a Function of the Levels of Certainty Required by the Task

The demands of the reading task probably also affect the reader's perceptual span. Different tasks place different demands on the certainty with which the reader must identify specific letters or words. Proof reading or checking for spelling errors lies at one extreme of the certainty continuum and skimming a long passage for a general idea at the other extreme. Does the perceptual span of the accomplished reader vary in accordance with the demands of the task? Does the span of the skilled reader contract for studying technical materials and expand when he is skimming? What classes of peripheral information are picked up under skimming conditions? Under what conditions can or does the poor reader vary his perceptual span? Will he pick up more information farther out in his peripheral vision if he is familiar with

the subject matter and language of the text? (Further discussion of the effect of familiarity of the text can be found in section 3 below). Can flexibility be trained? Given no decrease in comprehension, eye-movements could be used as indices of the success or failure of such training.

RECOMMENDATION: The NIE should support investigation of the allocation of attention within the stationary field of fixation and the temporal distribution of information intake during fixation.

Until very recently the psychology of visual perception assumed that the visual system operates passively given adequate illumination of the retina. That is, it was assumed that input in vision occurs continuously and that all parts of the stationary visual field are processed instantaneously and simultaneously. While there is now much psychological and neurological evidence that this eye-as-a-camera assumption is not correct, there is as yet little agreement as to what processes do occur. It is certain that the visual processes are several and complex, and the evidence available indicates that vision is much more active and intentional than previously assumed. Some of these processes are of fundamental importance to our understanding of visual information processing as well as to disabilities and dysfunctions which affect reading ability.

Foveal Information Versus Focal Attention or Centration

The retina of the eye is classically divided into two gross areas: the fovea and the periphery. It is sometimes held that in common with these structural differences the visual processes are optically fixed so that the information falling on the fovea is thoroughly processed while the information falling upon the periphery can only be crudely, "preattentively" processed. This view is now known to be oversimplified. The structural and functional distinctions between the more sensitive central area of the retina and its surround and the complexities of the processes involved do not support a simple dichotomy into two systems. The peripheral areas have been found to be more sensitive than previously believed. Most importantly, perhaps, the evidence now appears uncontrovertible that focal attention is not fixed by the structure of the eye but can be directed at will to any area, foveal or peripheral, within the viewers' visual field. In addition, viewers seem able to adjust the size of the field to which they attend with accompanying differences in the amount of detail processed.

Piaget (1969) uses the term perceptual centration to refer to the act of focally attending to a sample of information and the term perceptual decentration to refer to the act of resampling or broadening

the centration to include more peripheral areas. Other terms have been used to describe similar processes. Relationships between Piaget's (1969) conceptualization of centration, Neisser's (1967) and Kahneman's (1973) concept of focal attention, Mackworth's (1965) experimental demonstration of tunnel vision, and the discussions of attending broadly in Woodworth and Schlossberg (1954) are suggestive but by no means clear. The basic distinction between foveal information and perceptually centrated information, however, has been experimentally documented in several ways. Engel (1971), Grindley and Townsend (1968), and Keeley (1969) demonstrated that deliberate attention to a certain peripheral area increases visual acuity in that area, and Fraisse, Ehrlich, and Vurpillot (1968) showed that focal attention increases the apparent size of objects in peripheral vision. Indeed, a comparable phenomenon was reported by Helmholtz (1925) early in the century. Furthermore, subjects can exert voluntary control over perspective reversal in a reversible-perspective figure which is presented to the eye as a stabilized retinal image (see Hochberg, 1970a). These studies demonstrate that attention can be directed within the fixated visual field, and there can be little doubt that the process is an important one in visual information processing, particularly under the stimulus density conditions of the printed page.

Focal Attention in Reading

An exploration of the role of focal attention or centration within the reader's visual field holds important ramifications for theory and research on reading. A number of investigators have suggested somewhat different attentional functions to account for the growing evidence that the fixated visual field is subjected to systematic sampling by the visual systems. Such functions are fundamental to the scan path hypothesis proposed by Noton and Stark (1971), to the expectancy functions proposed by Hochberg (1970b), and to the suggestion by Geyer (1966) that input in reading is accomplished by a left-to-right attentional scan at a rate of 8 msec. per letter space, among others. Unpublished research findings tending to confirm the 8 msec. per letter space rate and detailing the neurological functions in the retina responsible were presented to the conference by Dr. Derek Fender.

Further research is necessary to examine the allocation of focal attention within the fixated visual field, to discover the rules by which the sampling of the fixated field proceeds and the circumstances under which the rules are over-ridden or altered. Does the reader of right-proceeding text, as in English, direct attention to right peripheral information while the reader of left-proceeding text directs attention to left peripheral information? If so, can this tendency be readily reversed? Do the order and direction of attentional sampling precisely follow the spatial sequence of the fixated text or can the

sampling more flexibly adapt to the needs and expectancies of the reader and the characteristics of the text? Is there a change in the extent to which focal attention is directed to peripheral areas as a function of level of development or of reading skill?

It seems likely that these attentional input functions are related to certain forms of reading disabilities associated with laterality differentiation and characterized behaviorally by reversal difficulties. Such cases are common in reading clinics, but the causes of such difficulties are only now becoming known. Considerable work remains before the systems responsible will be fully understood and diagnostic and remedial procedures developed. There can be no clearer example, however, of the importance of theoretical work to eventual clinical and educational practice than that provided by these newly-discovered visual functions.

The Timing of Information Intake During the Fixation

A classic experiment by Sperling (1960) utilizing a partial report technique in a situation which preserved the stationary field for a second or longer (and a host of later experiments using the same technique) demonstrated that subjects have considerable purposive control over the spatial aspects of the field and that visual intake itself, in some sense, is a discrete act under the temporal control of the viewer. Since under tachistoscopic conditions intake requires a fraction of the time devoted to the average fixational pause in reading, the question of when during a fixation does intake occur becomes significant. It now seems unlikely that intake always occurs during the initial portion of a fixation, as long assumed. There is some reason to suspect that intake may occur most typically just prior to the saccade, that is, in the latter portion of a fixation. A third possibility would hold that intake occurs flexibly where needed and may take place during any temporal portion of the fixation. This question holds important ramifications to our understanding of the apparent stability of the visual world and relates to the need to maintain a temporal balance between processing systems in reading (Geyer, 1966).

McConkie suggested during the conference that by using a computer driven cathode-ray tube display it would be possible to present the text for a limited period of time following fixation and then to mask the display with another pattern. By varying both the duration of text presentation and the time of onset of presentation during the fixation and examining the degree of disruption of reading that results, it may be possible to answer many questions concerning the normal temporal distribution of information intake during fixations.

2. Considering Moves

RECOMMENDATION: The NIE should support research on the peripheral visual and cognitive controls over the timing and extent of a saccade. What guides and directs an individual's eye-movements?

Given that our eyes receive fine-grained information only with the small foveal area, we can learn about the visual world efficiently only through a succession of eye-movements or saccades. Since it is impossible to pick up much detailed information in peripheral vision, multiple fixations and the eye-movements that produce them are necessary in extended displays and are therefore an inherent part of the reading process. Probably all intake of visual information occurs during fixations since it is generally believed that visual input is suppressed during a saccade either as a result of retinal blurring or as a result of a central inhibitory process (Haber and Hershenson, 1973; Volkman, 1962; Volkman, Schick, and Riggs, 1968). Furthermore, the saccade is considered a ballistic eye-movement whose trajectory cannot be altered once it has begun (although this unalterability is presently under debate). The accurate hitting of a pre-selected visual target is a phenomenon of some neurophysiological interest and should perhaps be considered developmentally (see section III, A) but of more relevance for this discussion is the way in which the target is selected. What directs the reader's saccades? How is the target for a saccade selected?

There have been various theories posited regarding the guidance of the eye in reading but most involve some combination of the following three positions (see Rayner, 1974). The first argues that the skilled reader develops a rhythmical movement pattern fixating, on the average, an equal number of time on each line of print (see Tinker, 1958, 1965). Although this uniform pattern theory was once popular, little empirical support for it exists.

The second position supports stimulus control of eye-movements and contends that targeting of saccades is determined by information acquired from the periphery. In picture-viewing tasks, the evidence is compelling that fixations are not random or uniform but are directed to selected parts of the display most likely to be informative (Mackworth and Morandi, 1967). This indicates that display features detected peripherally act to guide where the next fixation will (or will not) fall. Although peripheral control over eye fixations occurs in picture scanning, we do not know at present the extent to which peripheral control operates in normal skilled reading. Since reading involves many aspects which pictures do not, including semantic and syntactic components, generalization from studies using pictorial displays may not be valid. Tachistoscopic studies of word recognition have

found specific letter information, initial and final letters, word shape, and letter grouping or spelling pattern information to be useful in identification (Havens and Foote, 1963, 1964; Gibson, Pick, Osser, and Hammond, 1962; Marchbanks and Levin, 1965; Woodworth, 1938). Moreover, word shape and initial and final letters have been shown to affect reading behavior (McConkie and Rayner, 1973a; Rayner, 1974). Research is needed to define what cues are picked up peripherally in reading and to determine how these cues are utilized for guiding future fixations.

The third position on eye-movement guidance emphasizes internal control mechanisms. Internal control models presently appear in two forms: one which emphasizes the deductive or guessing-game aspect of skilled reading (Goodman, 1970; Levin and Kaplan, 1968) and a second which emphasizes the inductive or information-seeking aspect of reading (McConkie, 1973). The first model states that the reader makes a hypothesis about what will come next and moves his eyes to confirm his hypothesis. The second model asserts that the reader may have some expectations about what comes next, but he does not guess and confirm; instead, he looks in the area of the sentence with the highest probability of giving information. He seldom looks at the beginning of a sentence or at blank spaces in continuous text (Abrams and Zuber, 1972; Rayner, 1974). Research should be directed towards clarifying the relative importance of the deductive and inductive aspects of reading. Their relative importance may vary with developmental and individual style factors.

The most reasonable model describing guidance and control of eye-movements involves a combination of the stimulus control and internal control positions (Hochberg, 1970b; McConkie, 1973). The decision of when to move and where to move one's eyes may be dependent upon an interaction of semantic constructions, hypotheses, and anticipations based upon information assembled from previous fixations and peripheral syntactic and semantic cues present in a current fixation. Information acquired from successive fixations constrains the alternatives that the reader expects to confront, and makes identifications easier during later fixations. Knowledge of language rules and contraints, redundancy of the text, knowledge of the subject matter, and peripheral and semantic cues allow the reader to recognize a word on the basis of less foveal information than if such knowledge and cues were not present and/or not utilized.

If we consider the targeting of eye-movements to depend upon both cognitive and peripheral control systems, certain specific research questions may be asked: At what point in the processing of information during a fixation is the command given to initiate the next saccade? Are semantic constructions completed before the eyes move on? If not, is the targeting of the next fixation determined independently of the semantic interpretation of the current fixation? If peripheral cues are important in eye movement guidance, is the poor reader and/or

beginning reader unable to take advantage of these cues? Does peripheral cue usage change with respect to the skill level of the reader or does it vary with familiarity of the foveally fixated item or the peripheral items? Can we write or structure text so as to facilitate peripheral cue usage and increase the speed with which text can be processed?

A controversial and speculative version of the combined internal and stimulus control model suggests the notion of preplanned programs of multiple eye-movements (perhaps three or four fixations) which might be overruled by "stop" or "modification" signals resulting from text encounters. Research would be necessary to determine the extent of the pre-planned programs under various reader and text conditions (e.g., age, skill, complexity or density of the text) and the characteristics of the over-ride rules which permit changes in the program.

3. Considering Orchestration of Stops and Moves

In skilled reading the eye does not have to bring every letter close enough to the fovea that its shape is recognizable; nor, in viewing pictures, does every detail in the display have to be fixated in order for the viewer to know what the picture contains. The displays are sampled, and the specific pattern of eye-movements determines what is actually sampled. This fact makes eye-movements central to skilled visual information processing.

In viewing text a good reader reads about 240 words per minute; an excellent reader, about 400-500 words per minute; a "speed reader", of course, may read many times faster. There are these limiting factors, however: (1) the maximum average rate of saccades and (2) the range within which letter shapes can contribute to word recognition. The maximum average rate of saccades in any looking behavior is about 4 per second, or about 240 fixations per minute. The good reader, therefore, at 240 words per minute, is reading about one word per fixation and the excellent reader about 1.7-2 words per fixation. Since the average word is between 5 and 6 letters in length, the faster rates clearly exceed the perceptual span of 6 letter spaces within which we can expect individual letter shapes to contribute to word recognition (see section 1. above for perceptual span discussion). An examination of actual reading records will show many long words, perhaps 12-15 letters in length, that receive only a single fixation. Thus, skilled reading, because it is a sampling procedure, is necessarily constructive in nature, with the reader interpolating between the glances that are actually made and forming anticipations about information to be brought by subsequent fixations. Just what is being constructed and what the anticipations are may be studied through analysis of the orchestration of saccades and fixations -- their number, order, duration, and placement -- in response to cleverly manipulated text.

The economy with which a text is sampled is in part a function of the viewer's knowledge about the world, his knowledge about language, his assumptions and intentions with respect to the reading task, and his familiarity with the text being sampled. The more knowledgeable the viewer, the more skilled his hypothesis-forming and testing procedures or his information-compiling abilities and the better his guesses about what the text is "saying." The pattern of sampling employed in reading text, the orchestration of stops and moves of the eyes, may be analyzed to study the nature and interaction of the factors contributive to the sampling decisions and to assess the individual's stage of development and expertise in the abilities that underlie skilled reading. With real-time eye-movement records, one could also analyze where the reader had <u>not</u> sampled and then determine what inferences he could make about non-sampled areas based on what was sampled.

Two points concerning methodology seem appropriate to this section. Obviously, different experimental designs are required for probing different questions. But if we want to understand the processes operative in normal <u>continuous</u> reading, then such reading should be represented among the experimental approaches. At the beginning of paragraphs or isolated single sentences, an abnormally large number of fixations and of regressive movements are made. It is therefore important to collect eye-movement records of entire paragraphs or of a single test sentence embedded in a paragraph. This is especially critical if we want to investigate the relation between eye-movements and the form in which meaning continuously evolves <u>across</u> sentences and paragraphs in normal reading. Secondly, if we are concerned with the retrieval of meaning from continuous text, eye-movement records may not provide sufficient information for a complete picture of the phenomena involved. Information from other dependent variables (e.g., comprehension tests) must be adduced to supplement the interpretations of eye-movement records.

<u>RECOMMENDATION:</u> The NIE should support research that tests the generality and boundary conditions of the proposition that where the eye looks at any moment reflects the item of information that is of particular importance in cognitive processing at that moment.

The specific recommendations set out below (and many put forward in sections II, Pictures and Graphic Displays, and III, Television) assume, with varying degrees of explictness, that the orchestration of fixations and saccades of the eye reflect on-going cognitive processes and that the eye looks at the visual information that is of particular immediate importance in processing. To the degree that this assumption is meaningful and true, eye-movement research will contribute immensely

to the study of reading, picture scanning and television viewing, in particular, and to the study of language comprehension, problem solving, and thought processes, in general.

When we control experimental situations in such a way as to require (a) that the subject must obtain the information in the exact order that he needs it, and (b) that in order to obtain the information he must fixate on or very near the specific part of the display which contains each item of information, then the assumption is self-evidently and trivially true.

However, the relationship is not always so simple. For example, we know that attention may be shifted from one time to another when the eye itself does not change its position accordingly (see the discussion of focal attention in section I above). Moreover, because of the rate limitations of the movement of the eyes in many cases eye-movements cannot possibly follow the processing order completely.

Nevertheless, what is particularly impressive is the evidence that even when there is no need (in terms of the extrinsic situation) to fixate a particular item, subjects will do so. They will fixate visual items approximately at the same time as those items are being heard (Cooper, 1974) or are being processed for meaning (Carpenter and Just, 1972). It would be extremely important to be able to analyze the processes of comprehension by recording a subject's gaze; however, the boundary conditions within which eye-movements will serve this purpose should be established.

Some researchers have investigated this issue by means of simulation procedures in which the normal information gathering glances, self-programmed by the subject, are replaced by sequential presentations administered by the experimenter. The intent of these procedures is to find presentational sequences which interfere minimally with the reading of text or the perception of pictures and which must, therefore, approximate the sequence of information acquisition provided by the subject's eye-movements under normal viewing conditions. Bouma (1974) proposes on the basis of such simulation experiments that eye-movements proceed at a rate that is only loosely related to the rate at which cognitive processing proceeds and that individual eye-movements are not determined by the ongoing cognitive process. This proposal cannot be accepted in its strong form: The regressions that often are made to specific places in reading the text (Geyer, 1966), and the direct evidence of the effect of an unexpected foveal view on the duration of that very fixation (McConkie, 1974; McConkie and Rayner, 1973) are clear examples of direct relationships between ongoing cognitive process and the associated eye-movements. These results are clear examples of the fact that no simulation procedures, or indirect research, can in the final event replace direct eye-movement measurement. But Bouma's general point is tenable and more direct research to the point is needed.

RECOMMENDATION: The NIE should support research which examines the orchestration of saccades as a function of the goal and state of the reader.

The Influence of the Reader's Goal on Eye-Movement Patterns and on the Meaning Extracted from Text

Although not much explicit research on the issue is available, it would seem that for any given reading material eye-movement patterns are highly influenced by the purpose for which the passage is read. The goal, "read as fast as possible and get the overall idea," generates a pattern of eye-movements totally different from the goal, "read carefully to make sure that you do not disagree with any specifics of the writer's meaning," even though the reader and the reading material could be the same in the two cases. Yet very little research has been conducted aiming to make explicit and to clarify the differences in eye-movement strategies and the meaning retrieved under the constraints of the different goals, i.e., by the different implicit task definitions or self-instructions.

Although introspection may suggest that for any given text the number of different implicit goals the reader could pursue is very large, task analysis of the reading process might reveal that these many different goals can be reduced to a few goal types, each type calling for a different optimal eye-movement orchestration and reading strategy. A skilled reader should have learned appropriate strategies for the different goal-types and be capable of flexibly altering the number, duration, and placement of his fixations as a function of the reading goal. It is quite possible that many so-called poor readers are actually over-specialized readers in the sense of not having acquired a sufficient variety of reading strategies. Woodworth (1938) claims that slow readers use a uniform fixation per line ratio as well as a constant fixation duration regardless of goal or text complexity. This issue of practical and theoretical importance is in need of investigation.

The Role of Subvocalization

The reader's goal may not only be achieved through the appropriate orchestration of stops and moves of the eyes but also through covert oral behavior or subvocalization. Research by McGuigan and his associates has shown that during the silent reading of both children and adults, lip and chin activity as measured by electromyography increases relative to control (rest) periods (McGuigan, Keller, and Stanton, 1964) and that improvement in a child's reading comprehension as a result of remedial training yielded increased covert oral behavior

(McGuigan and Shepperson, 1971). Covert oral behavior during reading reduces in electromyographic amplitude with age but persists significantly in the adult reader (McGuigan and Bailey, 1969). McGuigan (in press) argues that covert oral activity is beneficial to the reader because it facilitates internal information processing. In this role, subvocalization may act as an attention focuser; for example, auditory presentation of prose and backward prose during reading resulted in an increase of speech muscle activity (McGuigan and Rodier, 1968). It might be concluded that covert oral behavior acts to slow down reading so that more complete processing may occur; however, McGuigan and Pickney (in press) have found that "speed reading courses" produce heightened activity of the tongue during silent reading, contrary to expectations.

Further research is recommended to elucidate the interaction among covert oral behavior, the pattern of eye-movements, the goal of the reader and the meaning obtained from text. Such questions as the following might be asked: All things equal, how does covert oral behavior relate to a reader's eye-movement orchestration? Given the same comprehension level (varying from acquisition of detail to general idea), do slow readers and speed readers differ in subvocalization activity? What is the effect of text characteristics (e.g., complexity, familiarity) on the above complex of variables?

The Influence of the State of the Reader on the Orchestration of Saccades and Fixations

Factors like emotionality, anxiety, learning blocks, and fear on the negative side and motivation or interest on the positive side might significantly affect sampling behavior as well as perceptual span and the use of peripheral information. One theory (Easterbrook, 1959) postulates that an increase in arousal leads to a restriction of the range of cues the organism uses in guiding action. When appropriate action involves a discrimination between relevant and irrelevant cues, the discrimination is impaired under conditions of increased arousal, and there is a reduced ability to focus on the relevant cues (see Kahneman, 1973). Also, there is some indication that high arousal may lead to a greater lability of attention; it may lead to an increase in scanning which may in turn be related to an increase in distractibility. On the other hand, extremely low arousal may lead to a failure to adopt an appropriate task set or a failure in the evaluation of one's own performance (see Kahneman, 1973). With respect to reading in particular, overarousal (caused by fear of failure or anxiety) might lead to a restriction in the range of cues used by the reader, effectively eliminating peripheral visual information, or it might contribute to an erratic sampling pattern, a random orchestration of stops and moves. Is there an optimal level of arousal for an individual for efficient execution of a particular reading intention?

The measurement of psychophysiological phenomena in conjunction with eye-movement recording would contribute significantly to this type of research. A general level of arousal could be determined through such measures as galvanic skin response or heart rate. However, a close correlation between these measures and eye-movement parameters are a problem since the response latency of the eye is much faster than that of most psychophysiological variables. However, an individual's response on grip pressure and pupillary dilation measurements is sufficiently quick to allow reasonable interpretation of simultaneous recordings of these arousal variables and eye-movement behavior. Careful research in this area may be very fruitful.

RECOMMENDATION: The NIE should support research which explores the nature, duration, and sequence of the component processes involved in reading and the integration of these component processes.

The skilled performance of a complex act such as reading requires the execution and coordination of a great many component processes within a very short period of time. As is characteristic of complex skilled performances, the sequencing and integration of these component processes is not open to introspection, and the final product -- comprehension of the written passage -- provides us with little information on how that product was achieved.

A number of different models of the reading process and of its component skills have been advanced (e.g., see Geyer, 1963, 1972; Mackworth, 1972; LaBerge and Samuels, 1974). It is not the purpose here to subscribe to one of these models, but rather to point out the value of eye-movement research for testing and extending the models of reading and its component processes. What is needed to elucidate these processes is (1) a means of monitoring the reading act during its execution and (2) various experimental stimulus manipulations aimed at probing the operation of the component processes. Eye-movement recording answers the first need and the second need is discussed below.

Stimulus manipulation was suggested by several consultants at the conference and elaborated upon by McConkie as one means for clarifying the nature, duration, and sequence of the component processes in reading. At a certain position in a passage different letter strings or words might be embedded, each of which would produce an error which would be noted only at a particular level of processing. It is likely that such an error would produce an irregularity in the reader's eye behavior (e.g., unusually long fixation or regression), and eye-movement records would indicate when that irregularity occurs. Levels of processing which might be explored in this manner include recognition of letters or words, text segmentation, identification of case role of a word

group, integration of the meaning of the present clause with the total passage information, etc. "Errors" -- atypical words or constructions -- might be embedded at any of these levels.

McConkie (personal communication) has found that fixation durations seem to increase when a non-word letter string is first encountered, not a fixation or two later. These data suggest rather rapid processing at this level. But McConkie reports that processing even beyond this level may occur extremely rapidly. Using reaction times, Isakson in McConkie's laboratory found indication of a greater processing load (as evidenced by longer reaction times) at points in the sentence where he expected the meaning of a phrase to be integrated. His reaction time probe suggested that semantic and syntactic information from one fixation might be processed rapidly enough to help determine the location of the next fixation. Eye-movement data (especially fixation durations) would have provided important evidence for this integrative function and for McConkie's tentative conclusion that information can be processed to the level of identifying case relationships and integrating meaning within a relatively short time -- probably one fixation. This general technique of altering text in various, carefully specified manners to determine where and if eye-movement irregularities occur would seem to have potentially high payoff for reading theory.

A second means of exploring this issue (implied to some extent in the first) uses fixation duration to probe the nature of the mental operations underlying comprehension. Just and Carpenter (1971) report that, overall, fixation durations on negative sentences are longer than those on affirmative sentences. Gould (1973) has also demonstrated a relationship between fixation duration and mental operations in a Sternberg scanning task. He asked subjects to memorize a set of digits (e.g., 2, 4, 6) and then to look at each digit in a visual array to determine if any of them were in the memory set. The time spent looking at each digit was proportional to the size of the memory set, and thus reflected the mental comparison of the fixated digit to each of the memorized digits. In continuous reading of a prose paragraph, it might be that comparisons of fixation durations at various linguistically or semantically defined portions in the text would be suggestive of particularly complex, numerous, or integrative mental operations.

A third technique which has been used to advantage by Kolers (1968, 1972) is the alteration and distortion of text in order to study the strategies that subjects use to read them. This third technique, like the first described, adopts the strategy of distorting the normal situation in order to investigate the effects of the distortion on the typically rapid, highly automatized process of reading. The effect on the skilled reader of manipulation of the orientation of letters, lines, or entire passages has been investigated, but there are numerous other variations which might be used to break down or slow down reading in different ways -- e.g., exaggerating the separation between the letters within words or the words within a line of print, deleting

punctuation, printing the passage in vertical rather than horizontal lines, etc. Since transformations impose differing constraints, comparing the effects on eye-movements of the various transformations could help to identify the component processes involved in reading.

Component Processes During the Acquisition of Reading Skill

While the sequences of component processes are run off rapidly by the skilled reader except where problem areas of text are encountered, for the child or the beginning reader these component processes are probably learned somewhat independently (or hierarchically) and gradually integrated as skill increases. For example, for the beginning reader, the act of decoding sequences of letters into words requires a substantially greater allotment of attention and a substantially longer period of time than does decoding in the skilled reader.

Some recent analyses of reading focus on the capacity of short term memory in suggesting that the slowness of decoding is a critical factor in decreasing the comprehension of beginning or slow readers. According to this analysis, poor readers fail to comprehend because they are engaged in reading parts of words one at a time and integrating the parts into whole words overloading the short-term memory system and thereby making it impossible to integrate the information obtained from each successive word.

Another, probably complementary, conceptualization of the relation between decoding and comprehension focuses on the allocation of attention to various of the component processes combined in reading (LaBerge and Samuels, 1974). When the child or beginning reader must concentrate on decoding from a visual to a phonological code, the attention he can devote to integrating semantic units as he proceeds is limited. The skilled adult reader, on the other hand, may be able to attend almost entirely to meaning, while decoding proceeds automatically. Thus the manner in which the component processes function together may be quite different in the beginning and skilled reader. Indeed, in one study (Guthrie, 1973) correlations among subskills were high for good readers but were low for poor readers.

For the beginning reader who is also a child, the capacity of short-term memory or the capacity to re-allocate attention among the component processes of reading may be developmentally limited, and these limitations may in turn restrict the child's ability to integrate peripheral and foveal information. It has been found that for adults, the acquisition of information from peripheral vision speeds the processing of that same information when it is subsequently fixated (Sanders, 1963). Can children use peripheral information as effectively as adults? Does the use of peripheral information vary with its location in the periphery, its saliency, and/or the complexity of the peripheral stimuli?

Research using the techniques described above with readers at different levels of development and of skill acquisition may clarify the specific component processes which provide problems and must be attended to at those different levels. Comparisons of children and illiterate adults during learning to read might be particularly useful in factoring out age and skill constraints on the process of reading.

RECOMMENDATION: The NIE should support research which explores the encoding and construction of the message as a function of the knowledge system of the reader and the linguistic and semantic characteristics of the text.

The manner in which a reader scans and samples text is influenced by and reflects his familiarity with the content (both the vocabulary used and the objects, events and relationships symbolized) and with the linguistic structures of the text. If content and linguistic structure are familiar, the reader's anticipations and expectations about the text yet to be encountered are likely to be confident and accurate and he will proceed with more widely spaced samples of the text. With familiarity it might be that a "deductive," anticipatory reading strategy is emphasized over a more purely "inductive," information-gathering strategy.

A number of research techniques were suggested during the conference as means to explore the relation between the subject's scanning strategy and his familiarity with the content and linguistic structure of the text. For example, the pattern of eye-movements made while reading a paragraph or story could be compared (1) after having heard the paragraph read verbatim, (2) after having heard a differently-worded version of the same paragraph, (3) after having viewed a pictorial representation of the paragraph's "message," and (4) with no prior exposure to the content and linguistic structure of the paragraph. To what extent is visual scanning different in these four conditions? Patterns of eye-movements could also be compared (1) on text previously dictated by the child or adult (for which there is no uncertainty concerning familiarity of linguistic structure and content), (2) on unfamiliar text equated in vocabulary, content difficulty and syntactic structure, and (3) on unfamiliar text which is considered to be slightly more difficult (in content, linguistic structure or both) than that dictated. In sum, comparisons of eye-movement patterns on text which is systematically varied in content and linguistic structure across readers who vary in linguistic and semantic knowledge may be fruitful. Such research could provide solid information concerning the value for beginning readers of texts constructed with a familiar dialect and familiar content. Furthermore, it might suggest optimal ways to broaden grad ually the linguistic and semantic repertoires of the beginning reader.

In addition, more research is needed on the effect of linguistic variables, per se, on reading. Early eye-movement studies of reading (see Tinker, 1958; Woodworth, 1938) gave little systematic attention to the relation between linguistic variables and the locus and duration of fixations. A few recent studies, however, have addressed such questions and have shown that skilled readers selectively fixate specific linguistically defined areas within the text (Comunale, 1973; Kennedy, 1967; Mehler, Bever, and Carey, 1967; Wanat, 1971, 1972; Zarger, 1973). It would be interesting to study the development in early readers of appropriate within-sentence fixations.

Little is currently known about the effects of linguistic structure on the pattern of eye-movements, and linguistically-oriented research may provide significant information about the ongoing processes of reading. Across subjects with varying linguistic repertoires, of varying linguistic competence and reading skill, what effects do ambiguous sentences or such linguistic constructions as active-passive verb forms, embeddedness, negation, and agent-nonagent forms have on the orchestration of eye-movements (i.e., on the number, order, and duration of fixations on specific portions of the text)? What are the various demands that such linguistic forms place on the information processing systems? What is the relation between different parts of speech (noun, verb, adjective, etc.) and fixations? In addition to helping us acquire a general knowledge of the influence of linguistic factors on eye-movements, this research direction may have particularly high pay-off in assessing differences between ages in sensitivity to (and comprehension of) various linguistic constructions and in comparisons of the scanning patterns of readers who are bilingual, bidialectal, or for whom English is not a primary language.

It is well documented that groups who speak a dialect variant of standard English or a different first language are disproportionately represented among those with reading problems. However, there are few concrete data on the processes of reading and of learning to read in these populations. Research on the reading of bilinguals currently focuses either on adults who fluently speak and read both languages (Kolers, 1966; 1970; 1972; Macnamara, Feltin, Hew, and Klein, 1968) or on bilingual children who are not having reading problems (Lambert, 1972; Lambert and D'Anglejan, 1973). Eye-movement data may provide critical information on group and individual differences in the sampling strategies bilingual or bidialectal readers use to gain information from written material, in relation to what the readers comprehend verbally. Do the good and poor bidialectal readers differ in their attention to highly informative portions of the text? Do the eye-movement patterns of the bidialectal reader differ when he is reading "standard" versus dialectal text? Research of this sort might yield knowledge about which syntactic constructions pose special obstacles to those reading a dialect or a language other than their own, and such information would have clear implications for instruction.

RECOMMENDATION: The NIE should not support the wide-scale use of eye-movement data as a diagnostic indicator of reading deficiency given our current knowledge base.

For some time it has been known that the eye-movement patterns of a poor reader differ from those of a good reader. Poor readers make more fixations, more regressions, and have longer fixation durations than good readers (Gilbert, 1953; Taylor, 1937, 1957; Taylor, 1965; Tinker, 1965). However, before eye-movement data can be useful in the diagnosis of reading difficulties, they must provide additional information to that which can already be obtained more easily through the use of traditional reading tests. The research recommended above could indeed generate such information; but until the research has been done, eye-movement recording will not significantly advance the cause of more accurate diagnosis. It does not require eye-movement records to make gross differentiation between good and poor readers.

Children and adults read at different levels of skill; however, reading skill as diagnosed by achievement tests (or by gross eye-movement characteristics) constitute little more than assignment of individuals to ordinal categories. While we can locate educational problems and issues through such comparisons of individual performance, previous experience has shown that we do not thereby understand the nature of the problems. More differentiated, fine-grained categorizations (e.g., through the use of subscore profiles on reading achievement tests) go further toward a more adequate approach. They allow specification of a diversity of forms of good and bad reading. This is important, because not all bad reading has a common source and not all good reading takes the same form.

However, these categorizations rely on the assessment of performance outcomes. What is needed in diagnosis is a measure which provides information on the processes involved in reading, on which processes are deficient and how they are deficient. We need to focus on what Glaser (1972) has termed the "new aptitudes," by which he means not the outcomes of learning (which are assessed by traditional aptitude tests) but individual differences in the way children learn, in the processes they engage in a learning situation. Eye-movement data can provide more precise information on the processes of reading than can tests which differentiate only on the basis of performance outcomes. Although its potential has yet to be fully explored, eye-movement recording may offer a technique for determining more precisely what components of reading are most problematical to an individual reader. The optimal use of eye-movement records, however, requires a theory and empirical data correlating eye-movements with the cognitive processes involved in reading. Once theory about the moment-to-moment processing has been more fully articulated and has been related to the eye-movement patterns during reading, it will then be possible to examine departures from the theoretical norm in eye behavior and to relate those in turn to

variations or deficiencies in cognitive processing as reflected in the eye-movement pattern. More accurate and more useful diagnosis of reading problems may then be possible.

Thus it seems probable that eye-movement recording could, in the future, prove most useful in the identification of specific problems in reading. This is not to say, of course, that the solution to the problem will lie in retraining eye-movement. Only in a minority of dyslexics does it seem likely that the movement of the eye, per se, may be the cause of reading problems. Appropriate experimental designs using carefully selected populations could clarify the relative importance of "abnormal" eye-movements as a cause and "abnormal" eye-movements as a reflection or symptom of problems in reading (Benton, 1973; Flax, 1973).

RECOMMENDATION: The NIE should support studies which examine the factors in text which facilitate the initiation, maintenance, and direction of active looking and facilitate learning or message retrieval.

Whether one looks actively and selectively at text and how one sustains the effort over time depend on many factors including characteristics of the individual (e.g., goals, state, cognitive style, reading skill), external factors in and apart from the text, and interactions of these two.

The manner in which the skilled reader samples normal text during reading and the various influences on this sampling were discussed in previous sections. The positive role of peripheral visual information in guiding subsequent saccades was emphasized. However, the information on the page which is available in peripheral vision, but which is not immediately necessary for understanding the text, might also serve as a distraction and could conceivably interrupt an ongoing scan of the relevant text. For example, attending to the lines above or below the line of print which the reader is currently encoding could disrupt the reading process. The successful reader must selectively attend to only that information in peripheral vision which is immediately relevant.

Some recent research has addressed the question of distraction by (or the amount or degree of processing of) information in the irrelevant lines of a passage. Neisser (1969) and Willows (1974) used a selective reading procedure in which relevant lines of a story were separated by lines of "irrelevant" words. Measures of the speed of reading the passage and intrusion errors suggested that material on the "irrelevant" lines is processed to some extent under some conditions; moreover, good and poor readers were affected differentially by the "irrelevant" lines. The use of eye-movement data in connection with such dependent measures as the speed of reading, comprehension, and intrusion errors would be

useful in exploring how the irrelevant text is attended. Are the irrelevant lines actually fixated upon, and if so, how often and when? If the irrelevant material is not fixated, are there changes in the pattern of eye movements on the relevant text (e.g., longer durations, shorter saccades) which would indicate that irrelevant material was being processed? How far in the vertical periphery can the material appear and still have an effect? These questions would be particularly interesting in comparisons of readers with varying reading skill. How does irrelevant peripheral information interfere with the beginning reader or poor reader as compared with the skilled reader, with the younger child as compared with the older child?

A complementary set of questions concerns the types of variations within the relevant text which attract, sustain, and help direct selective attention (Tinker, 1965; Zachrisson, 1965). Research is needed in this area to yield understanding and control of the attentional value of text; until recently decisions on such matters have rested on the intuitions of the writer, the editor, and graphic designer. On the practical side, every step that we can take to make the text more attractive to read and more easily assimilated reduces the necessity for extrinsic motivators and for "will power" on the part of the reader.

Such reading programs as Words in Color, DISTAR, and i.t.a. assume that color cues, diacritical marks, or controlled orthography will facilitate reading acquisition. These claims need objective empirical evidence and it is possible that eye-movement research can provide it. For example, if these programs aid the beginner to become a skilled reader faster, then he should show skilled reading eye-movement patterns (i.e., less regressions, more saccades, shorter fixations) earlier with these cued materials than if taught with the same materials without cues. What are the changes in eye-movement patterns as the child progresses through the Words in Color program, for example, as compared to the patterns of the child learning to read the same text without color? How do eye-movement patterns change when the i.t.a. learner is transferred to traditional orthography?

Another untested assumption is that the child first learning to read needs material printed in large type. If this assumption rests on a supposed underdevelopment of the child's visual system, the assumption is probably untrue since the five-year-old does not have a foveal visual acuity problem (Peckham, 1933). Perhaps large type places less strain on the child in production of the small controlled linear saccades required by the reading task, but this has not been shown. Perhaps large type makes it easier for the beginning reader to make fine discriminations between the distinctive features of individual letters, but again empirical evidence is lacking. More generally, there is a need to assess the appropriateness of specific typographic presentations for specific reading tasks (e.g., learning to read, skimming, studying, oral reading) and for specific kinds of text (e.g., technical writing).

Experimentation with type size and spacing between "units" using eye-movements as a dependent variable may yield reading materials that ease the load on the beginning reader or give him a better attack on print. For example, smaller print and larger spaces between words might allow a whole word to be foveated at one fixation and eliminate interference from the periphery. Conversely, graduated spacings might encourage attention to relevant peripheral cues and might assist the reader in chunking larger syntactic units. How do inter-unit spacings interact with developmental changes and different stages of reading skill acquisition? Are some spacing techniques better for certain textual materials than others? How are comprehension and reading speed affected by spacing devices?

Type size, diacritical marks, color, and spacing are only a few of the possible graphic devices which might be varied in order to facilitate the initiation, maintenance, and direction of active looking, and to improve reading skill, comprehension, and/or speed. For example, beginning reading material might employ increased saliency of certain phonic units, certain words essential to the message, or certain syntactic units fading out the saliency as reading skill advances. There are also a number of graphic techniques which might be used once reading skill has been acquired: marginal notes, exdented as well as indented section beginnings, large or extended capital letters to indicate sentence beginnings or the start of new sections, more liberal use of headings in the text, alternate lay-out and compositional styles which complement the organization of the text, extra white space between sentences combined with occasional indicators for especially important material.

The effectiveness of the above suggestions about future and current typographical cueing practices in reading materials is testable through eye-movement monitoring and should be considered with the reader's skill level and reading purpose in mind.

B. PICTURES AND GRAPHIC DISPLAYS

Research directed toward the scanning of pictures and graphic displays is important, both independently and in connection with text or spoken language. Pictorial material constitutes an important educational medium. Pictures (in the form of comic books, TV, picture-book illustrations, or photographs) reach viewers who, because of age, motivation, or functional illiteracy, do not normally read text. In addition, pictures provide a means of studying the processes of perception and comprehension, and the development of these processes, with subjects for whom textual material is inappropriate.

Many of the individual recommendations which were made for textual material can and should be extended to pictorial material as well. Questions concerning the size of the perceptual span, peripheral visual

and cognitive controls over the timing and targeting of a saccade, and the orchestration of fixations and saccades are equally applicable, in some form, to picture scanning as well as to reading.

As is true of skilled reading, much of picture interpretation is constructive in nature, with interpolations being made between samples of information and with the viewer forming anticipations about the information to foveate next. In viewing pictures, the evidence is compelling that fixations are not random, but are directed to selected parts of the display that are likely to be informative (Mackworth and Morandi, 1967). This indicates that certain features of the display are detected by peripheral vision and are used to guide the eye to its next fixation. Moreover, while the order of fixations is often different for different individuals, there is good agreement in the frequency with which particular features are fixated and with the durations of the fixations (Mackworth and Morandi, 1967). In general, during the initial period of viewing a picture a few relatively large saccades (ca. 4 1/2°) are made to points that are highly informative. Fixations at these points are relatively brief (ca. 250 msec). Subsequent excursions are progressively smaller and fixations are longer; by the tenth fixation they are about 3° and 300 msec respectively (Antes, 1974).

The economy with which pictures and other graphic displays are sampled is in part a function of the viewer's knowledge about the world and about the structure of pictures, his assumptions about the looking tasks, and his familiarity with the picture being sampled. The eye-movements thus provide a means of studying the factors which contribute to the sampling decisions made during viewing. There are three main research areas where the recording of eye-movements made in response to pictorial stimuli and graphic displays may be particularly useful; they are described below.

RECOMMENDATION: The NIE should support research which explores the effect of age on the acquisition and use of visual information presented in pictures and graphic displays.

Research on visual scanning holds an important place in current theories of perception, attention, and cognitive development. These theories emphasize both the significance of scanning as an indication of the sequential organization of selective attention (e.g., Haber and Hershenson, 1973; Kahneman, 1973) and the role of scanning in the construction of mental representations (e.g., Hebb, 1963; Jeffrey, 1968; Noton and Stark, 1971; Piaget, 1969; Zaporozhets, 1965). Within the contexts of such perspectives, eye-movement data provide information on the plans or strategies of subjects for acquiring visual information and on the mental representations which may be under construction as the scanning proceeds.

Developmental studies using eye-movement recording during picture scanning are currently few in number (Cohen, 1974); however, scanning-oriented studies using other dependent variables suggest systematic changes in visual scanning with age. It appears that adults, in comparison with children, more readily adapt their scan strategy to meet the requirements of the task, focus on more informative details of the stimulus display, conduct a more organized (exhaustive and/or efficient) scan, are less subject to disruption from task-irrelevant visual stimuli, and can better integrate portions of a stimulus when shapes are presented in segments over time (Day, 1974). Some of these trends are worthy of study, refinement, and elaboration using eye-movement recording.

Familiarity of the Stimulus

Familiarity with the stimulus materials and with the task requirements may be critical in some of the age-related differences which have been found (Day, 1974). When confronted with a visual form or scene that is familiar, younger children exhibit eye-movement patterns more like those of older children (Zinchenko, Chzi-Tsin and Tarakanov, 1963), and the eye-movement patterns of adults who are scanning complex, unfamiliar stimuli may resemble those typically considered characteristic of children (Zusne and Michels, 1964). There is a need for research to assess at various ages the changes that occur with increased familiarity of shapes and scenes.

Selective Attention

Research should be conducted which will explore children's ability to attend selectively to task-relevant aspects of visual displays under various conditions of "noise" (irrelevant stimuli) and of attentional support. A number of developmental studies have indicated that young children's performance on visual scanning tasks is affected more than that of adults by particular characteristics of the visual stimuli (Day, 1974; Gollin, 1961; Wohlwill, 1960). Younger children, in comparison to older children and adults, benefit more from stimulus characteristics that help to structure visual scanning and appear to be more distracted by noise in the visual field. While there is a growing literature on visual selective attention (e.g., Hale and Morgan, 1973) memory for various aspects of the stimuli is the dependent variable which is typically used. Memory is quite far along in the information processing sequence, and memory report may be influenced by many factors in addition to initial attention. Eye-movement data will permit observation of the initial acquisition of visual information.

Furthermore, the use of eye-movement data in connection with other dependent variables can probe whether, with age, there is an increasing ability for cognitive reorganization of information that was acquired

in a particular visual sequence. Measures of fixation sequence would yield knowledge about how the information was taken in; then questions could be asked about children's memory for the information, integration of the information acquired, and their flexibility in mental recombinations.

Since learning from educational materials is contingent upon selecting and attending to educationally significant information, research on visual selective attention ultimately should contribute to the design of pictorial and graphic materials and of educational environments which attract and sustain attention to educationally significant materials.

Scanning Patterns and Plans for Information Acquisition

Because the scan sequence is assumed to reflect the child's plans for acquiring visual information, careful observation and analysis of the scan sequence may allow formulation of the rules and plans used at various ages for problem attack (see also section III, C). When the child's plans or rules are understood, it will be possible to explore the flexibility of the rules used by children of various ages and the effects of instruction. Can the child be made aware of a better set of rules? Will he be able to shift his fixation sequence correspondingly? How flexible are children of different ages in restructuring the scan sequence on the basis of newly acquired visual information?

Abstractness of Representation

Eye-movement research will be useful in investigating age-related changes in response to different types of pictorial stimuli such as photographs, line drawings, or abstract designs. It is known that young children recognize two-dimensional representations and that prior experience with two-dimensional representations is not essential for such recognition (Hochberg and Brooks, 1962). However, there appears to be little literature on children's differential responses to various types of two-dimensional representations and on the extent to which children must "learn" to read pictures of various types. If there is a developmental progression in the acquisition of picture-reading skills, is it related to a representational continuum? How much abstraction can be tolerated by young children? There is a need to determine the effect of various types of representations on the scanning patterns of children of different ages and on their ability to recognize and acquire meaning from them.

RECOMMENDATION: The NIE should support research exploring the optimal use of illustrations and text in combination.

The exact function of illustrations in a book of text is a matter of some debate. The dominant view is that in most books for skilled readers an illustration is an aesthetic appendage, although in books such as technical journals or how-to manuals, illustrations (in the form of pictures, diagrams, maps, or charts) may be used to convey information supplementary to that presented in the text. In books for children and unskilled readers, it is assumed that illustrations may serve a more critical function. They may help the reader to establish the meaning of a word or of a difficult passage, and, perhaps more important, they may arouse his curiosity and interest, facilitating the initiation and maintenance of attention to the text. Furthermore, a wide body of literature now attests to the fact that the appropriate use of pictures seems to facilitate learning and retrieval (Paivio, 1971) for both children and adults.

However, illustrations may not always facilitate attention to the text or function to sustain reading. Pictures may allow the reader to obtain meaning without reading, or they may distract his attention from the printed text. Currently there is little information about the interactions between illustrations and text and their most useful balance. The use of eye-movement recording to indicate when the reader/viewer looks at the text and when (and where) he looks at illustrations may provide the basis for a workable approach to this important topic.

Research should be designed to examine the relation between the scanning of combined illustrations and text and comprehension of the message and memory of the content. It seems likely that use of the first dependent variable (scanning) in combination with one or both of the latter two (comprehension and memory) will be maximally fruitful. Such research should consider characteristics of the text and illustrations including the following (a) the type of information conveyed by each; (b) the relation between the information conveyed by each (e.g., are the two redundant or do they supplement each other?); (c) the complexity of the text and of the illustrations; (d) the relative location of the text and illustrations; (e) the saliencies of the text and illustrations; and (f) the concreteness or abstractness of the text and the illustrations (e.g., photograph versus line drawing versus abstract illustration).

RECOMMENDATION: The NIE should support research directed towards the assessment of verbal comprehension.

Comprehension is difficult to measure at best and is even more difficult to measure in the case of very young children or of adults who are not skilled in verbal expression. The need to measure verbal comprehension is especially acute for those who cannot read. The Study Group on Linguistic Communication suggested that one desirable alternative to norm-referenced assessment of reading skill would be

comparison of a given individual's listening comprehension with his reading comprehension. Such a comparison would reveal the degree to which an individual's potential for reading is being realized. For the comparison to be made, however, it is necessary first to know the limits of that individual's comprehension of spoken language. Furthermore, if we want to ensure that textual material matches the student's level of comprehension, we must be able to measure that level.

Recording of eye-movements in response to pictorial material may offer a technique for probing speech comprehension. Under circumstances that have yet to be fully elucidated, subjects appear to fixate those items of a picture that are salient in their cognitive processes of the moment (see Chapter 3.I.A.3).

Cooper (1974) reported that, under certain circumstances, fixations appear to be spontaneously controlled by the meaning of currently heard language even when the acquisition of visual information is unnecessary. When subjects are simultaneously presented with spoken language and a visual field containing elements which are semantically related to the ongoing oral language, subjects tend to look spontaneously at those visual elements most closely related to the meaning of the language currently heard. This technique is characterized by an extremely rapid saccadic response to elements of the heard language, but, ideally, it appears that this rapid response may not disrupt the ongoing language processing.

Using a paradigm in which visual information was necessary to the task, Carpenter and Just (1972) probed the type of internal representation which the reader derives from language by presenting the readers with a sentence or question which had to be verified or answered by acquiring visual information from a picture. They predicted that subjects would internally represent "few" (a negative quantifier) differently than they would internally represent "a minority" (an affirmative quantifier). Indeed, they found that the location of the first fixation on a pictorial display varied as a function of the manner in which the two quantifiers were internally represented. Although Carpenter and Just used written language, the same technique could be employed with spoken language.

This procedure, once the limits of its efficacy are understood, offers a prospect of the greatest importance. If the phenomenon is stable and if experimental situations can be devised in which this method reliably reflects the subject's internal representation or interpretation of spoken language, it will offer a powerful tool for probing verbal comprehension.

II. PROCESSING TELEVISION DISPLAYS

RECOMMENDATION: The NIE should support the exploration of moment-to-moment information intake and processing mechanisms involved in the encounter of the child or adult with television. This is a research priority of highest order, for which eye-movement technology is a sine qua non. The general needs are: (1) to record the sequential behavior of the eyes (saccades, fixations and smooth pursuit) as well as the point of regard of the subjects' eyes on the televised display; and (2) subsequently to relate this pattern of eye behavior (a) to moment-to-moment analyses of the dynamic stimulus and (b) to theoretical conceptions about the operation and development of assimilatory mechanisms, short-term memory and/or processing, and the elaboration of knowledge.

Television is increasingly relied on as a medium through which information of complex and subtle sorts is provided to very large numbers of people of all ages, from all social groups. 96 percent of American homes today have television sets; over 90 percent of households with incomes less than five thousand dollars have at least one set. For a large proportion of literate Americans television has come to rival, if not supplant, the print media as a source of information about the world. For the pre-literate child and for the non-literate adult the importance of television is even greater.

Television is increasingly relied on as a medium of instruction, both in school and at home. For pre-school children in particular, and for all people to some degree, all television is instructional, whether or not it has been so designed. The power of television to teach a deliberately designed curriculum, and its cost effectiveness in delivering that instruction, have been amply demonstrated and have led to the remarkably rapid growth of instructional television in the past decade. In the future, much wider use of the medium for instructional purposes is sensible and inevitable.

Television has been successfully used as a medium for reading instruction. Certainly for beginning reading instruction, and possibly for more advanced instruction, television has unique capabilities for making the printed code accessible to the learner. Increased use of television to teach and to motivate reading is desirable and probable.

Considering the ubiquity of television sets, the endless hours of television viewing and the impact of television on every facet of contemporary life, from pre-school education to electoral politics, it is

startling to discover the poverty of theory and the paucity of empirical information about how information is received and processed from television.

There is a general need for descriptive studies that examine not just what information people extract from television but how they extract and process it. We need to investigate the ways in which people of all kinds extract information of all kinds from television displays of all kinds. Television is a dynamic medium in which sequences of images and sounds are presented over time. It must be perceived and understood as it moves. The need is for research which can monitor the viewer's responses as they occur in real time. Eye-movement research, for reasons set forth earlier, has clear advantages in this regard, yet eye-movement recording has been little used.

Considerable research of other kinds has been done on television (see Lesser, 1974 for a review). Studies have investigated, for example, the social effects of television, the extent and patterns of use of television, and the instructional effectiveness of particular programs. But all of this research says nothing about the moment-to-moment processing of information by the viewer while he is watching.

Nor has television been thoroughly researched for its intrinsic power to teach. Research on instructional television has tended to measure achievement of the educational goals of particular programs rather than investigating how these gains have been achieved or why they have not been realized. That television does teach is quite well documented (Ball and Bogatz, 1973; Briggs, 1973; Fowles, 1973; Rovet, 1974); but how it teaches, the processes by which the outcomes have been achieved, the extent of its instructional limitations, the degree to which it is unexploited and (perhaps the key question) the relationship between the elements of the televised message and the viewer's perception and cognition have had but light interest from capable researchers.

There have, however, been small and encouraging beginnings. An extremely useful body of formative research, done principally by Palmer and his colleagues at the Children's Television Workshop, has begun to explore questions such as those this chapter proposes be studied. Formative research of this kind is rarely published, since it is usually rapid and informal, performed with small samples, and addressed to program-specific issues (see Palmer, 1972). Nevertheless, the work done by researchers at CTW and by others under its sponsorship clearly indicates that these questions are amenable to systematic investigation, and that the results of such investigation would have profound implications for improving the quality of effectiveness of instructional television. Of particular relevance to this report are the studies by O'Bryan (1975) using eye-movement recording techniques in studies of viewer responses to The Electric Company. Results of these eye-movement

studies have led directly to changes in program design and raised questions of considerable general importance, for example, about individual differences in responses to televised images.

We recommend that NIE support research on the acquisition and processing of information from television for four reasons: first, because television is a mass medium of communication whose structure has not been adequately investigated despite the fact that it is ineluctably there to be studied; second, because the unique inherent characteristics of the medium shape the very nature of the messages transmitted on it, the way in which those messages are received and processed and the cognitive structures of the viewer; third, because the special properties of the medium have unique value for direct and indirect instruction; and fourth, because television can reach and teach several of the populations with whose particular needs NIE is especially concerned. The four sections of this chapter correspond to these four points. Their sequence is not arbitrary: as understanding grows of the structures of televised messages and their special properties, more enlightened research can be done on how those messages are received and processed by viewers and on the nature of the cognitive structures produced. This can lead in turn to more informed use of the medium for instruction generally, for reading and other essential skills particularly, and for addressing the information and education needs of special populations of viewers.

A. ANALYSIS OF THE MEDIUM

Television, considered as a medium independent of any particular content, is a conventionally organized system of mass communication, the meaning of whose elements is shared by its audience. It is in this respect like the print media, and the Himalayan reason for studying reading (because it is there) applies as well to television. The conventionally agreed-to elements of the television "code" and quasi-syntactic rules according to which those elements are combined are used deliberately and consistently by those who make television programs; but they have yet to be subjected to any systematic formal analysis. Since television is so widely relied upon as a source of information, it is important to discover precisely what are the conventions by which messages on this medium are organized and understood.

<u>RECOMMENDATION</u>: The NIE should support the articulation of theoretical analyses of the elements of the television code and the structural rules by which those elements are temporally and spatially combined, and research to test and refine these analyses.

Television combines sound and visual images which move in time. Television is therefore temporally organized: there is a temporal

sequence of sound and a temporal sequence of images. The two sequences obey different but occasionally complementary organizational rules which govern the combination of visual and auditory elements. Makers of television observe the rules quite scrupulously in order to ensure the intelligibility of their efforts.[3] Fine distinctions and choices are made between very similar shot sequences in the knowledge that the distinctions are real and the choice will affect the message communicated. For example, a director can elect to cut from a wide shot to a close-up of an item of interest, to zoom in optically on that item while the camera remains stationary, or to move the camera itself closer and closer to the item of interest until it fills the screen. Each of these variations communicates a subtle but identifiable message. The cut to a close-up respects the viewer's sensed need for a closer look but the impact of the close-up will vary with the intensity of the need as determined by the dramatic context. The sudden zoom in, on the other hand, carries its own dramatic weight, and conveys a sudden and surprised attention to an element within the wider field of view. (A sudden zoom out is an infrequent device except in live coverage of unscripted events where it often is simply the instinctive reaction of an individual cameraman to having momentarily lost his place in the event. Here again, the visual effect conveys a clear message to the viewer: the appropriate detail has been lost, resulting in momentary confusion; and there is a need to recentrate the entire scene and to reallocate attention within it.) The dolly in to a close-up has the effect of moving the viewer as well as the image; the camera is the viewer's surrogate and is briefly endowed with the mobility the viewer himself might have were he in the scene he is watching.

Elements of the sound track are combined in similar, rule-governed ways. The choice of on camera or voice-over speech, of musical theme and instrumentation or of sound effects is made carefully in the knowledge that whatever choice is made will quality the message communicated.

As there are conventional rules by which visual and auditory elements are assembled into scenes, so there are conventional rules by which scenes are combined in larger segments of programs. Scenes begin and end in predictable, conventional ways, as do transitions between scenes. For example, if the viewer is to be led back in time through

---

[3]One soap opera director, for example, recognizing the necessary predictability of situations and shots in that dramatic form, developed a short-hand code for use in issuing instructions to his cameramen. A "Mickey Mouse" was a two-shot over the shoulder of the woman to the man seated next to her on the couch. A "Minnie Mouse" was the reverse shot, across the shoulder of the man to the woman. "Ring around the Castro" called for the camera to follow the rise and movement of one of the characters around that article of furniture.

the memory of a character in a television drama, the sequence introducing the flash-back might begin with a close-up of the character's face, his eyes directed away from, possibly above, the camera. The close-up may or may not go out of focus or begin to ripple slowly, but in any case there is a dissolve of images, not a cut, to the remembered scene. The dissolve will be immediately anticipated by and accompanied by a harp glissando or some other musical effect intended to convey that the action has now progressed to the interior of the character's mind.

Because the medium combines visual and auditory components in dynamic configurations of idiosyncratic detail, and because television is free to move in space and time, the viewer needs at each moment to be guided in his comprehension by the conventional rules of structure he has come to expect. The visual and auditory elements of the television code, and the conventional rules which organize their combination, are numerous, flexible, and subject to change. Some have derived from earlier film shooting and editing procedures. Increasingly, as the electronic technology of television develops and as understanding of its potential uses grows, the conventions of television become more medium-specific. The very flexibility to change of the conventional rules requires that they always be evident, since the structure of the message must be clear if the content of the message is to be intelligible.

The structural rules of television must be articulated and analyzed if we are to understand the nature of this enormously powerful medium of mass communication and if we are to use it effectively for instruction.

Some efforts in this direction have been made (Gibbon and Palmer, 1970; Hochberg and Brooks, 1973; Rust, 1971; Salomon, 1972; Lesser, 1974; and Gibbon, Palmer and Fowles, in press), but they have been neither as systematic nor as exhaustive as necessary. Furthermore, with few exceptions, these theoretical analyses have not been tested empirically. A combination of eye-movement recording while the presentation is being seen and after-the-fact measures of recall and comprehension would be useful in this regard. Comparisons of these kinds of data across carefully controlled alterations of the presentations would permit testing and refinement of the analyses.

B. PROPERTIES OF THE MEDIUM AND PROCESSES OF THE VIEWER

The physical properties of television and the structural conventions by which units are combined in messages, condition the content of the messages themselves, the manner in which those messages are perceived, processed and stored, and the motivational and arousal effects of the messages. This notion is much acknowledged and little studied. Marshall McLuhan (1964) among others, has discussed the nature of the

the medium and its effects on the viewer's mind in some detail; but his metaphoric and hyperbolic discussions have yet to be presented in language attractive to science. In the absence of any other theoretical constructs, however, his assertions merit the effort of translation.

Television is itself a source of light (and sound), not merely a light image reflected from a screen. The light comes from a grid of phosphorescent dots which is scanned thirty times a second by a beam of electrons which excites the phosphors. The beam is modulated so as to cause certain dots to phosphoresce more strongly than others, creating a recognizable image on the screen.

Because of the small size of the television screen only a small amount of visual information can be provided at a given moment. Because of the low resolution of the display, sitting close to the screen does not increase the amount of detail that is available to the viewer; in fact, it may actually decrease the information he can receive. Therefore, in order to present a scene or situation with sufficient richness of detail to make the presentation informative, close-up images of important objects like faces must be presented in fairly rapid succession. These close-ups are periodically punctuated by wider shots which assist the viewer in assembling the smaller views into a coherent reconstruction of the entire scene.

Thus, the physical properties of television have dictated the essential form of the messages transmitted on it. The physical properties of the medium and the resulting basic structure of the messages both obtain regardless of the content of the message. And they are present in live, video-taped, filmed, and animated programs alike.

It may be seen that there exists a rough analogy between the rapid succession of close-up images by which information is presented on television and the rapid succession of fixations made by the eyes in acquiring information about the environment. This analogy, and related considerations, should be explored. If the analogy holds, and if other analogous relations can be found to exist between the structure of the medium and the perceptual and cognitive structures of the viewer, television's effect on viewers may be powerful indeed.

RECOMMENDATION: The NIE should support eye-movement research that explores the moment by moment relations between the special structural properties of television and the perceptual, cognitive, and affective processes of the viewer. Such research should consider these relations as a function of the age, knowledge, skill, purposes, and cognitive style of the viewer. NIE should be prepared to support, as a part of this research, small-scale experimental production of television and film material and the design and production of computer animation that allows on-line modification of the stimulus while the viewer is watching it.

The sequence, rate, rhythm, salience, and comprehensibility of television presentations have been held to determine the degree and locus of visual attention elicited by the presentation and the level of arousal evoked. Both attention and arousal are likely to be reflected in the eye-movements that are made by the viewer.

The comprehensibility of the presentation may be related to the viewer's eye-movement governance in the following more complex way. The succession of close-ups necessary on the small screen to provide information about a larger scene must be integrated by the viewer into an assemblage or cognitive structure in which each of the informative shots takes its proper place in relation to the others. As has been suggested above, this sequence of shots simulates in a gross way the succession of views that would be received if the viewer had programmed his own eye-movements, directing his eyes in succession to the places from which information was to be obtained. If the succession of televised views is similar to those which the viewer would have received as a result of his own eye-movement executed inquiries and if the rate of presentation approximates the rate of acquisition to which the viewer left to his own perceiving would have been disposed, the scene should be rapidly comprehensible. With lessened correspondence to the viewer's own inquiries or expectancies, the comprehensibility should decline. On the other hand, the conspicuous absence of an expected view at the end of an otherwise comprehensible sequence may serve attentional and arousal purposes. For example, when the viewer is shown an actor's horror-struck face and is denied information about the image that evoked the horror, the effect may be to enhance the viewer's expectancy to the point of suspense. Attention, arousal, and comprehension, then, should depend on the extent to which the presentation approximates, or departs in orderly ways from, the patterns of perceptual search which are more normally maintained through the mediation of eye-movements.

If this analogous relationship between the viewer's perceptual process and the organized sequence of television images is found to be

true, it may be possible to study the perceptual process by manipulating the order and rate of the presentational sequence.

Because of the large spans of space and time which can be conveyed by the succession of disparate views on the small television screen, the structures that inform and sustain the expectancies must be larger and more general than those normally included in the concept of perceptual processing. The structures are cognitive ones, and the successful sequences of views may be successful because they model cognitive processing. That is, they may provide the sequential units of information in ways that are most compatible with the sequence in which the viewer is prepared to deal with them. Again, to the degree that this speculation can be supported by research, the reciprocal relationship would maintain: studying television sequencing would help us to understand cognitive processes at the developmental stage of the viewer, and understanding cognitive processes would help us to improve the efficacy of television instructional and communicative material.

Television's effects on arousal are worthy of study, for it appears that television messages, however intellectual their content, are heavily loaded affectively. Newscasters are preferred for their human qualities, not because of the news coverage they provide. Close-ups of faces are scanned attentively for indications of emotion even when the face is speaking of matters of challenging intellectual import. Actors in film and television know well the power of the close-up, and they allow it to do their work for them. The viewer empathically endows an impassive face with the expected emotion; an attempt by the actor to communicate the emotion with a facial expression, as he might on the stage, runs the risk of overstating and therefore falsifying the very emotion he seeks to communicate. The affective impact of televised images extends even to abstract shapes in animation. A triangle that has been made to dance has been given electronic life, and the viewer responds as he would to other living things seen on the screen.

Television's capacity for juxtaposing and combining fantasy and reality may have powerful effects on the cognitive structures of the viewer, especially the young child. Electronic effects such as chromakey -- a way of combining images from two cameras -- have the power to perform magic with apparently real images. A television character can talk to another image of himself. Scale cues can be deliberately distorted, making the actor appear huge or tiny relative to the surrounding set. The television screen provides, of course, a two-dimensional image, but usually that image is of a three-dimensional world. Chromakey, however, can place a live performer in a two-dimensional field. The curious effect that results shows a real three-dimensional person, removed from his three-dimensional environment and floating on the surface of the screen. This and other television devices may have the effect of blurring the distinctions between the categories into which experiences are sorted. The dancing triangle is no longer a symbolic representation of an abstract idea. It has been seen, and therefore known, as a creature with genuine, if fantastic, life. The flying nun can indeed be seen to fly; the credible, visible evidence

is there for the viewer to behold. Experiences such as these may frequently be taken to be real and true by young viewers, and may condition their responses in subsequent encounters with triangles, or nuns. Eye-movement research might inform such speculations. It might be inferred from eye-movement patterns, for example, whether a viewer is searching the screen for clues as to the nature of the magical event.

Implicit in the foregoing discussion is the assumption that the relations between the physical and structural properties of television and the perceptual, cognitive, and affective processes and structures of the viewer will vary as a function of the viewer's age and level of cognitive development, his knowledge of the rest of the world, his skill in interpreting visual and auditory messages, the purposes for which he is viewing, and his cognitive style. The precise nature of the variations, however, needs to be carefully explored. This suggestion appears separately listed below, but care should be taken to control for these factors in all the studies undertaken under the general recommendations of this section. There follows a list of questions for research. This list is by no means exhaustive, but rather illustrative of the range of topics to be explored.

(1) What television (or film) techniques reduce irrelevant data search and how is this reduction related to information processing and concept formation? Research to be directed at this question might include eye-movement and verbal report studies of such techniques as cutting, zooming, animation, bordering, etc. The data obtained would lead to the formulation of hypotheses regarding match-making between extracted process variables and presented stimuli. Can the material presented in the television sequence be made to approximate more closely theoretical processing limits imposed within the viewer? For example, Pascual-Leone's (1970, 1973) model of cognitive processing may be amenable to this type of investigation, since it enables predictions to be made concerning the amount of cognitive space required to process various information segments. These segments could be presented on television and/or film and the input measured by eye-movement and verbal report data. This type of study has implications for both modification of the cognitive space theory and for production techniques.

(2) Can or does television or film material alter visual and cognitive processing? Is there a structural change brought about as a result of viewing television? Are there differences in visual and cognitive processing either for television viewing or film watching? Are there differences in processing static images, real world data and dynamic television or film stimuli? Research approaches here might include comparison of eye-movement patterns generated among subjects on presentation of stimuli from the various modes mentioned above and concurrent data taken on recall, comprehension, etc.

(3) What are the effects of the various media on eye-movements per se? We are unsure of the impact on the eye control mechanisms caused by the physical or structural properties of television and

film. What, for instance, are the perceptual parameters of the "Zombie" viewer whose eye-movements seem to "freeze?" Is there a reduction in eye-movements on televised stimuli compared with static stimuli of similar content? Does the small screen presentation have any differential effect on parafovial or peripheral processing compared with larger screen presentations? Descriptive and comparative studies are a needed first step.

(4) What effect do techniques such as incongruity, denial of needed information, startle factors, tension building through stretching or compressing time have on viewing patterns? Do responses to these techniques provide insights into changes in visual or cognitive processing? How do they change expectancy patterns? Under what conditions do they increase or diminish learning potential? How do their effects vary with different viewers, with different viewing purposes? The type of research which might be undertaken could include studies in which the techniques were varied for different types of individuals and groups. Eye-movement patterns could be monitored to determine areas of particular fixation, information search, expectancy patterns and such. Allied with arousal measures and matched with other reports and observational analyses, these patterns might well provide very rich data which could lead to the sort of instructional theory development described below.

(5) What levels of affective reactions occur with variations of the type described above? What demands are placed on the viewer and how does he respond? How do varied rates and sequences of presentation affect eye-movement patterns and level of arousal? This research would coordinate points of regard with such psychophysiological measures as G.S.R. and E.E.G. The technical difficulties of such studies are formidable, but once the problems have been solved, the pay-off is likely to be high. NIE should be prepared to fund the development of this combination of technologies.

(6) What differences and similarities exist between children and adults of different ages, levels of development, degrees of knowledge about the world, reading skill, etc., in their viewing of television segments containing a wide variety of modes of presentation? Specifically, this type of study would attempt to classify groups of adult and child viewers according to cognitive style variables, ability variables, achievement levels, etc., and using eye-movements as the dependent variable, observe patterns of viewing produced by differential presentation of televised segments.

Experimental Production

Research of this kind, and of the kind described in the next section, is of limited value unless the researcher has the capability of manipulating and recombining stimulus elements. NIE should provide funds for editing existing televised material and for production on a small scale of experimental television material designed expressly to

meet the experimenter's needs. Computer-generated dynamic CRT displays which permit real-time, on-line manipulation of the image may provide a source of much useful pilot research. Manipulations carried out on computer displays can then be studied using more conventional television techniques under conditions of more sustained viewing. Here, as with research on reading, the limitations of simulation are firm. To understand television, we must do research on television.

Obtrusiveness of Measurement

The need is great to study television viewing behavior in circumstances approximating those in which television is customarily viewed. The scarcity of eye-movement data in studies of television needs to be remedied, and many useful studies can be done using presently available head-constraining eye-movement recording devices. O'Bryan reports that children approximately ten years old can easily accommodate to the obtrusive equipment. Nevertheless, there need to be eye-movement studies conducted in which the television viewer sits comfortably before the screen, undisturbed by a formidable laboratory setting. This is especially true for studies of young children's viewing eye-movements. The EG&G oculometer at the U.S. Army Human Engineering Laboratory, and possibly the head-free Honeywell oculometer (see Chapter 4 and Appendix), are the only instruments presently available which permit eye behavior to be monitored in an unconstrained situation. These instruments should be used for descriptive studies of eye-movements in response to television, especially with young children, and the data should be compared with other data on the same stimulus materials which has been obtained with more obtrusive equipment.

C. TELEVISION AS A MEDIUM OF INSTRUCTION

The third argument in favor of NIE's support of the study of television builds upon the first two: the conventional rule-governed structure of television messages, and the special perceptual, cognitive and affective properties of those messages endow the medium with a unique value for instruction.

RECOMMENDATION: The NIE should support research that explores the limits of television's intrinsic power to instruct, to model cognitive processes and to aid in the construction of mental representations. Such research should examine the instructional effects with respect to the characteristics of viewers. Small-scale experimental production should be supported. NIE should encourage research that relates to and advances the theories of instructional television.

It was suggested earlier that current theoretical conceptualizations of cognitive development regard visual search patterns as unique action systems by which objects and relations in experience are identified, and the storage of the programs for such actions is regarded as the basis for memory or knowledge. We suggest that televised sequences of images and sounds, organized as they are according to rules which may be analogous to the processes of perception and cognition, pre-organize the viewer's experience in a manner which facilitates its encoding and storage. If this suggestion is true, and it can be offered here only with the greatest diffidence, then the power of television to teach early, quickly, and effectively is awesome indeed.

Television has the capability of enlarging the viewer's repertoire of experience. It can transport the viewer in time and space, in fantasy and reality, to allow him to see, to hear, and to know remote people, things, places, and events. Animation and electronic effects allow him to experience visual representations of concepts and relations which are otherwise not amenable to direct sensory exploration. In each instance, the structural rules of the medium are applied in the design of the message. Whether the content of the program concern the mating of whales in the Gulf of California or the mathematical properties of space-filling curves, the viewer's perception and cognition are guided and sustained by the conventions of the medium.

The capacity of television to extend the viewer's experience to include parts of the tangible world he might otherwise not know has had powerful effects on the population of this country. Within the space of a few years we have been shown the Great Wall of China, the Kremlin, the moon, and a range of events that startles anyone who grew up in the absence of television: wars, assassinations, sports events from around the world, a presidential resignation, even an on-air suicide. We have come to expect of television that it provide us with these vivid experiences. Yet scientists concerned with learning and knowledge have examined neither the processes by which these vivid experiences are assimilated nor the shape of the new knowledge acquired. Both are worthy of detailed study. For example, given the variety of experiences available from television, it may not always be easy for the viewer to determine under what categorical rubric an experience must be stored. Leifer reports (personal communication) that an interview with one 13-year-old viewer, conducted to assess his skill in critical analysis of television, revealed that he believed The Rookies to be "more real" than the news. His argument was reasonable: The Rookies showed him events as they were happening, while the news reported them after the fact. This may or may not be an extreme case, but another tentative finding reported by Leifer underlines the importance of the issue. The young teenagers she has interviewed have been virtually unanimous in indicating that they watched television to learn. The Rookies is, of course, a learning opportunity just as important to the

viewer, if not to his teacher, as a Jacques Cousteau special. The former shows him important things, like how a gun works, how adult males communicate at work, how you talk on a two-way radio, or what a policeman wears after he takes off his uniform.

Television teaches all the time. We must discover why and how it does so, and we must discover in detail the products of the learning. Particularly we must investigate how the structure of the product relates to the structure of the presentation. Eye-movement studies are critical to this understanding. Through eye-movement studies we can discover the patterns of visual attention to the programs which can then be related in detail to the learning outcomes. Eye-movement patterns may, for example, reveal search for clues on which critical assessments are made about a program's reality or credibility.

Because television can be watched at home, it enjoys a special status as a learning opportunity. Unlike many school situations, television is non-punitive. Television shows to the viewer, but it doesn't see him; it speaks to him, but it doesn't listen. Television cannot judge the viewer's performance. This is of course both an advantage and a drawback: the viewer is not threatened by television and need not be apprehensive of his experience of the televised message; but the transmitter of the message has no way of judging the viewer's response and altering the message accordingly. The no-feedback character of televised communication makes research on television essential. At present the maker of television must rely largely on intuition to guide him in the design of his messages. Precise laboratory research and theoretical knowledge are necessary if accurate estimates are to be made about the degree and locus of attention being paid to the presentation moment by moment, and about how well the content is being comprehended. Two lines of inquiry must go hand in hand in order to achieve this end: (a) we need to know the factors that govern how attention is deployed within the display and the factors that determine how well the display will be comprehended, so that we can design the presentation well in the first place; (b) we need to measure how effective the instruction is in the laboratory situations in which we can obtain precise feedback about attention and comprehension. This will enable us both to estimate whether attention and comprehension will be achieved with the much larger distant audience from whom feedback cannot be received, and to correct and sharpen our theoretical models or proscriptors about how to manipulate effectively the factors that determine these variables.

If television's power to expand the viewer's experience of the actual is impressive, still more impressive is the capability of the medium to make sensorially available abstract concepts and relations. An example from Sesame Street may illustrate. One of the program's goals is to teach its viewers what a rectangle is; another is to help him learn to discover embedded figures in his environment. The two goals are combined in a deceptively simple segment. A wide shot is shown of the Sesame Street setting. The viewer is invited to look for

rectangles in the picture. After a moment, an art card outlining the rectangles is super-imposed, so that the rectangles embedded in doors, windows, and signs are made salient. Slowly, the image dissolves through to the art card along. The viewer now sees the rectangular figures extracted from the noisy ground of the street set, but in exactly the positions in which they were initially to be found. After another moment, the image dissolves slowly back to the super-imposition, and finally back to the original shot of the street. It should be noted that this otherwise undistinguished piece of production presents to the viewer an experience not available to him under any other circumstances. The segment does more than merely point out the rectangles embedded in the scene; it models for the viewer the actual process by which the geometric form is abstracted from its multiple noisy occurrences in the environment. At the moment when the rectangles alone are seen their commonality, and the principle which clusters them together as rectangles, can be seen. It seems unnecessary to suggest the value of eye-movement recording to examine viewer response to segments of this kind.

Not only can television model cognitive processes, it can assist the viewer in forming mental representations of the processes and the concepts formed. It seems likely that a young viewer of the segment described would scan the final wide shot of the street differently from the way in which the initial shot was scanned, not just because he now knew where the rectangles were hidden, but because his cognitive repertoire of representations of reality and his store of action systems by which to explore reality had been enlarged.

There is at present no theory of how learning from television occurs. Such a theory is badly needed if instructional television is to make full use of the medium. A theory of instructional television must be based on full empirical examination of the perceptual and cognitive processes engaged during the viewer's experience of television and a moment-by-moment relating of those processes to the features of the dynamic display.

Previous studies of learning from television have tended to collect after-the-fact data. Segments or full programs are shown, and only after their conclusion is the subject tested. Methods have included verbal reports (Fowles, 1973), observational analyses (Ahlwat, 1971; Liebert, Neale and Davidson, 1973), developmental analyses (Rovet, 1974), and multi-variable recall studies (Salomon, 1972). While this work is of value in assessing the overall outcome of programs it does not reveal the processes of learning as they occur in response to the dynamic stimulus. Studies which have attempted to assess viewer reactions during the course of the segment or program (De Vries, 1970; Liebert, Neale and Davidson, 1973) are few and have relied for the most part on observer checklists. Rarely indeed (Wolf, 1972; O'Bryan and Silverman, 1973; Briggs, 1973) has any part of the interaction of the subject with the program been directly observed in real time. In each

of these studies the viewing patterns of the subject were investigated by monitoring his eye-movements -- a procedure which appears to hold great promise for empirical study in the general research areas noted above and for the specific suggestions listed below.

(1) What are optimal time sequences for presentation of material? How may these be structured to direct looking behavior at the salient instructional content? These questions could be investigated by examining the eye-movement patterns of individuals and classified groups in response to segments varying in rate of presentation, length and complexity. It might be expected that low ability and/or low achievement groups would require instructional segments of less complexity, lower rate and greater length than other viewers.

(2) What are the relations of points of fixation to degree of recall of information or acquisition of skill? The research called for here would match the eye-movement patterns with various forms of information recall tests and tests of skill acquisition. This would provide useful descriptive information on the correlation of point of regard and apparent learning and could be especially valuable in modifying instructional programs to focus attention on primary components.

(3) When and how does live and animated action, sound-over, direct and indirect cueing, cutting, and zooming, etc., enhance or reduce eye-movement patterns on the salient stimuli? The research design might be initially formative, to revise and improve programs or segments by testing the effectiveness of various production techniques on the direction of attention as indicated by eye-movement patterns. Individual differences would be assessable through such research, and group differences could be studied as well. The medium makes possible stimulus modification and creates excellent opportunities for experimental studies.

<u>RECOMMENDATION</u>: The NIE should support research that explores the limits of television's power to teach and to motivate reading. Small-scale experimental production should be supported.

Television's special advantages for reading instruction, especially for beginning reading, derive from the properties and capabilities described above as having general value for teaching abstract conceptual relations. Printed language, as it is most often encountered, is static and unchanging. Yet the beginning reader must learn that this static representation encodes a most dynamic phenomenon: the stream of spoken language. He must understand that a particular arbitrary spatial arrangement of print corresponds to the temporal arrangement of spoken language. He must learn that the printed code is based on a complex and not readily perceived phonemic analysis of spoken language. He must learn that the correspondence of spoken phoneme to printed grapheme

is not always regular, that more than one speech sound can be encoded by a single letter or letter group, and conversely that a single speech sound can be written in different ways. Finally, when he has mastered all these strenuous analytic feats, he must forget them and resynthesize the elements of the printed code and the spoken language they represent so that meaning can emerge.

Television has the power of making the formidable principles of the printed code much more easily accessible to the beginning reader. It can do so for two reasons: first, because it can visably animate and manipulate printed elements of the code; and second, because it can present the animated code in synchrony with its spoken counterpart. For example, parts of words or sentences can appear serially as they are spoken or they can be moved apart and together in a visually concrete demonstration of the abstract analysis and synthesis skills that comprise blending. These techniques are also available to the classroom teacher with a set of flashcards and a pair of scissors. What television can do that the classroom teacher cannot is to animate as well as move the units of the code. Salience of words and parts of words can be achieved through color-keying, size distortion, flashing, etc. These devices serve to draw the viewer's attention to important parts of the visual stimulus, and they can be used in precise synchronization with the spoken sound track. Furthermore, they can be used dynamically: the cues can be introduced and then withdrawn within the same segment so the viewer is not implicitly encouraged to look for them or to rely on them in subsequent reading. Not all of these devices work equally well. Some cueing techniques, while attracting the viewer's gaze to the salient element may in fact distract him from the process to which he should be attending.

Studies by O'Bryan and Silverman (1973) and Briggs (1973) have indicated that eye-movement patterns are markedly responsive to differences in presentation of program segments in television reading programs and can be expected to vary substantially according to the subject's level of skill in reading. These studies, originally formative in nature, have occasioned program changes that have produced predicted changes in viewing patterns among poor readers and illiterates. Furthermore, there is some evidence (Mock, 1974) that these modified viewing patterns reflect a better attack by the learner on the presented stimuli and that this, in turn, leads to more effective learning of the instructional segment. However, this research is at a very premature stage, and further studies need to be conducted to provide a clear assessment of children's viewing patterns on dynamic reading instructional stimuli. Accordingly, the following research questions are indicated:

(1) What analysis and synthesis skills can be examined using eye-movements, and how does effective blending take place? Can viewing patterns be used to predict effective analysis and synthesis in reading static printed materials? This very complex area of human information

processing is particularly amenable to research using television presentation and eye-movement recording. Essentially, the research envisaged would relate the eye-movements of subjects watching dynamic presentations of word and sentence analysis and synthesis to their acquisition of the skills and concepts. It is likely that such studies could lead to the generation of new techniques of presentation and to substantial refinement of existing production methods.

(2) What is the effect of exact repetition of program segments designed to teach reading skills? Do subsequent repetitions cause viewers to change their scanning patterns? If so, does the change occur as movement toward more efficient eye behavior? Are saliencies more or less well attended over repetitions? How do these factors interact with age, skill, etc., of the viewer?

(3) Does television's capacity for dynamic presentation offer special instructional or research opportunities where metalinguistic concepts are concerned? Can the development of such concepts (e.g., the left-right sequence of letters and words; notions about the meaningfulness and functionality of written communication) be enhanced by purposeful programming? If so, it is expected that changes in the eye-movement patterns of the learners might reflect the acquisition of these concepts. Exploratory research will be necessary to determine the influence of individual and group differences upon the formation of these concepts. Subsequent experiments, using eye-movement patterns as dependent variables, could then aid in the formative evaluation segments designed to teach metalinguistic concepts.

(4) What approach and avoidance patterns are discernible in eye-movements directed toward printed stimuli? How may these be countered through production modifications? This research might investigate the ability of the medium to counteract avoidance of print by poor readers, especially by adult illiterates and non-readers. Eye-movement records could be taken to examine the effectiveness of program segments in directing the viewer's line of sight to the print and inducing attention to the critical or salient aspects of the print stimulus; the ability of the segment to overcome avoidance behavior might be directly tested, and elements of stimuli or modes of presentation which increased avoidance-type eye-movement patterns could be detected.

(5) How do eye-movement patterns of viewers skilled in reading televised reading instructional segments compare with their eye-movements on conventional printed pages? Are the skills modeled on television actually acquired and if so, how is their successful application in normal reading reflected in eye-movement patterns? What non-broadcast printed materials most facilitate the transfer of skills from television to the printed page?

D. TELEVISION AND SPECIAL GROUPS

Among the populations that television reaches and teaches are several whose particular needs are of concern to NIE. Television is accessible to a much wider diversity of people than is print. It is watched regularly by children at least as young as 18 months; it can be watched, and with minimal difficulty, by illiterate or aliterate adults for whom print is impossible or aversive; it is less language-bound than reading and is therefore, at least in part, accessible to speakers of languages other than standard English, for whom the vast preponderance of printed matter in this country may present problems. These viewers come uncoerced to this mode of communication, and indeed appear to find it intrinsically rewarding. Television provides them with an essential opportunity to obtain information about the world; if that opportunity is to be maximized we must better understand how these viewers presently use the medium and how the properties of the medium can best be exploited to meet their needs.

RECOMMENDATION: The NIE should support research that (1) investigates the moment-to-moment intake and processing of information from television by very young children, adult illiterates and speakers of language and dialects other than standard English, and (2) explores other potential informational and instructional uses of the medium to inform and teach these populations.

Very Young Children

Television has had a demonstrated, if not thoroughly understood, effect on the learning of children as young as three. Most of the available data on young children come from studies of Sesame Street and The Electric Company. The former program is addressed to preschool children from three to five years old. Initial assessments of Sesame Street (Ball and Bogatz, 1973) relegated three year olds to a small part of the total sample on the assumption that effects of the program were likely to be least evident in this younger population. Subsequent results indicated large effects in three year olds, possibly, effects with viewers as young as two. The Electric Company is addressed to seven through ten year olds, but audience surveys indicate that nearly half the audience, almost all of those who watch at home, are preschoolers. That three million preschool children should choose to watch a program of reading instruction addressed to second-, third-, and fourth-graders is startling indeed. At present, one can only wonder about the effects of such a program on young children, since there has been no systematic effort to study them.

Indeed, very little is known about what television programs are watched by young children or why and how they watch them. If any or

all of the previously discussed speculations about the relation between the properties and structure of television and the perceptual and cognitive apparati of the viewer hold true, these relations should have strong effects on the young viewer whose cognitive development is in an early stage, and for whom television's pre-organized material should be particularly attractive. These young viewers, engaged as they re in forming and revising predictive models of the operations of reality, must find television singularly easy to predict. Their experiences of television are therefore soon likely to be successful. Furthermore, their predictive failures never lead to the dire consequences attendant upon more immediate encounters with the real world.

If television is not only watched (as it has been observed to be) but closely attended to, by children as young as a year or eighteen months, then some of their predictive models of reality, initially constructed on the basis of their television experience, may be unfaithful to the nature of the rest of the world. Fantasy and reality are often indistinguishable on television, and the child's efforts to sort them out in life may be made more difficult if he is a heavy and early television watcher.

On the other hand, television can present the very young child with pre-organized experiences which may help him discover relations between objects and events which would not otherwise be perceivable by him until he discovered them unassisted and much later. Television may affect in important ways both the rate at which levels of cognitive development are achieved and, possibly, the nature of the conceptions acquired at various developmental levels.

Eye-movement studies of infants are exceedingly difficult to manage. Haith (1969) has observed the eye-behavior of newborns using infra-red light reflection and television cameras. It would be of interest to see whether newborns scan television pictures in the same way they scan real (or mirrored) images. Perhaps of greater interest would be the eye-movement behavior of infants, six months old and older, in response to television. This would require, of course, some highly unconstraining instrumentation, and in fact may not be presently possible. Nonetheless, if television is having effects on these young children, it will be difficult to infer them from other data; and as with older viewers, real-time process observations are necessary.

Adult Illiterates

Adult illiterates already rely heavily on television for information about their world. More deliberate use of the medium should be made to address their particular needs. O'Bryan has begun pilot studies of eye-movements of adult illiterates watching The Electric Company and suggests tentatively (personal communication) that the program may be most useful in giving them basic beginning reading skills. Other

reading programs designed specifically for this audience, and using the full armamentarium of television techniques, should be produced. When they are, formative eye-movement studies must be done as an adjunct to program development.

Television may play a less direct, but important, role in helping adults learn to read. Knowledge about the world is essential to reading; for reading ultimately involves extracting meaning from text in an efficient, comfortable, and rewarding fashion, rather than merely decoding letter strings into sounds. Television can provide that information to the illiterate, and enable him to break the vicious cycle that leads from illiteracy to general ignorance to illiteracy. Demonstrations of television's ability to motivate reading as well as to teach reading have already been made; but the potential of this extremely broad-gauge application has yet to be fully exploited.

Television already is used as an alternative to reading by most adult illiterates. This existing use of television should be built upon and extended. Educational and informational programs for adult illiterates could transmit most of the essential skills necessary to social survival and advancement. For these programs to be successful, however, more must be known about the purposes for which these viewers presently watch television and how they extract, process, and comprehend the information presented. Eye-movement studies will be essential to such research studies if they are to form the basis for subsequent program development.

Studies of how adult illiterates view and comprehend television will have a useful side-effect. It is difficult to identify and assess the comprehension skills of illiterates by any of the means conventionally used in school and classroom. Television provides a ready store of appropriate stimuli for use in comprehension studies with illiterates; and eye-movement recording, combined with post-exposure testing of other kinds, would permit much more precise and exhaustive data to be gathered than has heretofore been possible.

Speakers of Languages and Dialects Other than Standard English

Because of the relatively heavy emphasis on visual (as opposed to auditory) information on most television programs, it seems likely that many speakers of languages other than English watch and understand much of what is communicated. They may learn spoken English from those moments when a visual image is matched unambiguously with its language equivalent. Surely there should be more programs produced in the native languages widely used in this country, especially Spanish. But it could also be important to study how speakers of other languages process and comprehend programs in English. Results of these studies could be of significant value in altering information programs for general audiences so as to make them more informative to non-English

speakers. Programs that relied more heavily on visual information and less on spoken language could also be of value for deaf viewers. In any such program development efforts, the central role of eye-movement studies is clear.

Speakers of dialects other than standard English present an interesting population for television research. Almost all netwo k programming and most local broadcasting employ standard English speech; yet, in the absence of alternative programming, these programs are heavily watched by dialect speakers. It would be of interest to know how television is used and understood by these viewers, especially young children. Do young dialect-speakers, without other available sources, learn to process in-coming standard English from television? If so what visual referents do they use to confirm their understanding?

The design and production of television programs -- entertainment, information or educational -- has in general proceeded on the basis of the intuitive judgments of the makers. There has been little research and less theory. What research has been done has tended to assess main outcomes and gross effects. When formative research, addressed to more fine-grained analysis of effects, has been included in the design and production process, the programs have benefitted greatly. There is a need for more formative research of this kind. Given the persuasive examples of the value of formative research to instructional program design, it borders on insanity for any future instructional television efforts addressed to large audiences not to include a well funded formative research component. The cost of such research is miniscule compared to the cost of production, and the value of the results for better programs is incalculable.

The broader and ultimately more compelling need is for more basic and theory-based research on how people acquire, process and comprehend messages from television. This research could not only improve the quality and efficacy of television as a medium for the mass communication of information, but it might also reveal, in ways otherwise not discernible, the functioning of those perceptual and cognitive systems by which we encounter and deal with the world.

III. OTHER APPLICATIONS OF EYE-MOVEMENT RESEARCH

The previous two sections have focused on the use of eye-movement recording to explore processes involved in reading, picture scanning, and television viewing. Within each of these contexts, research has been recommended which probes both the information-processing mechanisms assumed to be common to all individuals and the differences and uniquenesses in the operation of those mechanisms which occur among and within individuals. This section considers the value of eye-movement research in exploring psychological states and processes not limited to those involved in reading, picture scanning, and television viewing.

Given the central role of vision in the adaptational economy of the human organism and the real-time connection between the behavior of the visual system and the higher cortical centers which control it, the range of studies for which eye-movement measures might be suitable is quite broad.

Relatively predictable visual behavior is found to occur as an accompaniment to task-oriented activity even when that behavior plays no specifiable role in the accrual of necessary information. As such, eye-movements serve as an index of a higher level process -- a kind of "psychomotor leakage of brain activity" -- rather than as an indication of what information is being sought from the visual environment.

One example exists in the tachistoscopic literature. Many stimuli are flashed at a subject too quickly for him to move his eyes. There is empirical support for the notion that, as he tries to remember each item his eyes move, in turn, to the position previously occupied by that item. A similar phenomenon is reported in the dream literature and by people who try to mentally reconstruct a visual scene. Their "internal" eye moves to areas they try to reconstruct. Since eye movements may reflect the sequence of mental processing of previously available visual information it may be possible to study cognitive analogues to the organization of visual scanning.

Eye contact is a behavior which frequently accompanies behavioral interactions but little careful experimental work has been carried out in this area. Yet, it has been claimed that eye-contact is the infant's first social response. Careful work in this area has shown that eye-contact by the baby with his mother occurs abruptly at 7 weeks of age. Nothing is known about the neurological accompaniments of this event, when it becomes specific to the mother (that is, when stranger-mother discrimination occurs), whether it reflects emotional accompaniments, depends on maternal treatment, etc. It is known that for autistic children, eye contact is a very negative event but no one knows how soon. Perhaps avoidance of eye contact could be an early indicator of autism.

Although extensive research has been carried out on the neurological base for eye-movements, the energizing mechanisms are not completely understood. Still, specific nerve deficits can be diagnosed by erratic eye-movements and there is a very substantial literature in this field. Moreover, eye-movements are very sensitive indicators of state of the organism whether states vary naturally or through the control of drugs. Hall, Rosenberger, and Monty (1974) have reported successful efforts to identify drug addicts by observation of their eye-movement patterns. It is widely reported that vertical eye-movements which require cooperation of both sides of the brain disappear before horizontal eye-movements which require energization from only one side when anesthesia is given. Little work has been carried out in humans in this area but it is known that newborn infants make, almost exclusively, horizontal eye-movements. One possible explanation is that such movements reflect residual anesthesia in the baby's system. An intriguing possibility for the use of eye-movements is suggested by work on newborn babies of drug-addicted mothers. The offspring of addicted mothers are also addicted and undergo typical withdrawal symptoms after birth, leading to death in the absence of treatment. The problem is how to determine appropriate dose levels. This might be done by monitoring the infants' eye-movement patterns.

These few examples of actual and potential uses of eye-movement research suggest that the observation of visual behavior should commend itself to investigators in a variety of areas of inquiry. The confluence of theoretical and empirical work on visual activity in a number of diverse disciplines has already enriched understanding in the fields of reading and visual information processing. Further cross-pollination of thinking is to be expected and should be actively encouraged by NIE.

The remainder of this section recommends research addressed to topics of more apparent relevance to the immediate concerns of NIE and of the conference from which the suggestions arose. However, this narrower focus should most emphatically not be understood to be preclusive of other applications of eye-movement research which are not recommended here.

Section A makes recommendations for research on developmental changes in the intake and use of visual information from a variety of visual stimuli. Section B considers the relation between individual differences and the intake and use of visual information. Section C suggests research that explores steps in problem solving and variations in those steps as a function of individual and group differences. The discussion in each of these sections is predicated on the fact that eye-movements are reflective of cognitive processes whenever any form of visual information must be or is acquired during mental activity.

RECOMMENDATION: The NIE should support research which employs eye-movement recording to explore psychological states and processes not limited to those involved in reading, picture scanning, and television viewing. This recommendation is based upon the assumption that knowledge relevant to such specialized processes as those involved in reading can eventuate from research which addresses more general issues in cognitive and psycho-motor development.

A. THE RELATION BETWEEN DEVELOPMENTAL CHANGES AND THE INTAKE AND USE OF VISUAL INFORMATION

RECOMMENDATION: The NIE should support developmental studies which chart the capability of the visual control systems of children of different ages.

Currently, virtually nothing is known about changes over age in the visual control systems of moves and stops of the eyes: ballistic accuracy of saccades, latency of response to peripheral stimuli, peripheral visual sensitivity, and the steadiness of fixations all may vary with development. Some research suggests that the child's ballistic accuracy may be less and his maintenance of fixation on a particular point less stable than the adult's (Piaget, 1969). Furthermore, there is a suggestion, though far from conclusive evidence, that children may have less peripheral sensitivity and a longer latency of response to peripherally-presented targets than adults (Lakowski and Aspinall, 1969; Miller, 1969). There is a need to consider the development of peripheral sensitivity with respect to the child's perceptual span and his ability to use peripheral information. Such characteristics of the visuomotor apparatus form the low level underpinnings of scanning behavior and are of major consequence in scanning tasks requiring precision and speed. Reading or the scanning of detailed pictorial material may require a greater control and accuracy of eye-movements than other tasks frequently confronted by the young child. We need to know at what age the visual control systems can be considered functionally mature. This information is essential for any eye-movement studies using children.

RECOMMENDATION: The NIE should support a limited number of semi-longitudinal studies of changes over age in children's scanning and processing of text, pictures, other graphic stimuli and television, comparing within subjects and within age groups.

The conference received several suggestions that the NIE support normative studies of eye-movements in reading and in picture scanning as a function of development. A contrary view held that such normative work was not efficient and that the highest payoff would come from a more limited set of careful studies designed to look at specific characteristics of eye-movements in relation to particular stimuli. Such normative data as deemed valuable might be gathered incident to experimental work with various populations of children, and inferences about developmental changes might be drawn from comparisons of sets of data collected in a variety of studies. The recommendation offered here constitutes a compromise between these two positions. It is recommended that "semi-longitudinal" studies be undertaken for several interesting populations of children -- avoiding any effort to try to resolve the demographic and theoretical problems involved in specifying a sample of children that could be regarded as "normal" or "normative." Such semi-longitudinal studies might use populations initially at 5, 8, 11, and 14 years of age, all studied concurrently over a span of three years. Eye-movement studies of these subjects would examine their changing responses to a variety of classes of visual stimuli. A long-term longitudinal study of a small sample of children should not be ruled out entirely, but before undertaking such a study careful consideration should be given to its advantages over the type of semi-longitudinal study proposed here.

One appropriate population for such semi-longitudinal studies would be the population of middle-class children who would actuarially be expected to become skilled readers, i.e., children who respond well to reading in school, who are encouraged by their parents to read, and who are found reading spontaneously. Another informative population for such studies would be bilingual children for whom some language other than English is dominant. A third population would contain children who are dyslexic and who show the Gerstmann pattern or some other pattern of definite neurological implication.

Semi-longitudinal studies of the acquisition of reading skill of such populations may yield important information for beginning reading instruction and the diagnosis of reading disabilities. Moreover, given the compelling quality of the comtemporary developmental or stage analyses, it would be of value to undertake such analyses with regard to children's uses of the media of education. We know that there are stages (i.e., sequential organization patterns which are at least moderately regular across children) in children's drawing A careful analysis might reveal such stages in children's scanning pictures, and might reveal relations between the way preschool chi n scan pictures or TV and their later acquisition of reading ski. Furthermore, data on the scanning of pictures, text, and television obtained from individual children across several years would allow assessment of intra-individual and of intra-age similarities and differences in the

scanning of the various media. Knowledge of such similarities and differences would make possible the enlightened selection of appropriate media of instruction for individuals and groups of children.

RECOMMENDATION: The NIE should support research which explores the relation between cognitive development and the intake and use of visual information.

The manner in which individuals scan their visual environment reflects their current knowledge of and expectations concerning the visual world and their purpose for looking. Since eye-movements are under strong cognitive guidance, they provide a significantly useful dependent variable with which to investigate developmental changes in cognitive processes. While several theoretical accounts emphasize an increase in systematic scanning with development, empirical data are scanty and more precise conceptualizations of the relation between scanning and cognitive development are needed.

O'Bryan and Boersma (1971), who have most systematically investigated the relation between scanning and cognitive stage, found significant differences in the eye-movements of conservers and nonconservers while they were engaged in a conservation task. Similarly, Venger (1971) found differences in the scanning patterns of children on a matching task, in which the subject was asked to match a rod to one of an array of stimuli arranged in order of increasing length. Where efficient scanning would have required an ability to comprehend transitive relations, the scanning of children typically considered too young to seriate was less efficient than that of older children. Vurpillot (1968) found scanning differences across age in subjects asked to compare two houses. Children over the age of six were much more systematic in their comparisons; and the scanning differences were at least partially a function of the different conceptions of "same" and "different" held by children of different ages.

The effect of development on performance in a variety of other cognitive tasks might similarly be revealed in the eye-movement patterns used to acquire visual information. For example, experimental paradigms using eye-movements might reflect the number of units (integrated assemblies of information or operations) which can be acquired and held in mind simultaneously by the subject, or the influence of the limitations of working memory on visual scanning (Pascual-Leone, 1970, 1973).

The use of eye-movements in combination with other dependent variables, such as judgments (e.g., same or different judgments) or verbal explanations, is highly recommended with respect to this research. Each dependent variable constitutes a single "window" through which the

psychological processes of the organism can be glimpsed. When the dependent variables used are solely outcome or product variables, only the end of an entire sequence of information acquisition and information processing can be seen. The more places along the sequence where measurements can be taken, where windows can be placed, the closer we will come to understanding the generation or construction of the final product. Eye-movements, which represent a rapid, real-time, continuous dependent variable, may be especially helpful in probing the relation between the acquisition and use of visual information during development.

B. THE RELATION BETWEEN INDIVIDUAL DIFFERENCES AND THE INTAKE AND USE OF VISUAL INFORMATION

RECOMMENDATION: The NIE should support studies of individual differences in the intake and use of visual information that may relate to educability.

In the study of individual differences (individual variation in cognitive processes and personality), the processes of attention and encoding are strikingly central to a number of different conceptualizations (see Kagan and Kogan, 1970, for a review). Distinctions between "reflective" and "impulsive" cognitive styles (e.g., Kagan and Kogan, 1970), between field-independent and field-dependent cognitive styles (e.g., Witkin, Dyk, Faterson, Goodenough, and Karp, 1962), between subjects expressing different degrees of "conceptual differentiation" (Gardner and Schoen, 1962; Santostefano, 1964a, 1964b) have implications for and/or have been revealed in the different ways subjects scan and mentally represent their environment. For example, it has been reported that field-independent subjects scan a stimulus more extensively than field-dependent subjects (Conklin, Muir, and Boersma, 1968; Witkin et al., 1962), and it has been reported that the comparison strategies (as revealed in eye-movements) of reflective subjects differ from those of impulsive subjects (Drake, 1970; Zelniker, Jeffrey, Ault, and Parsons, 1972; Ault, Crawford, and Jeffrey, 1972).

Nevertheless, most techniques for assessing individual differences have relied on dependent variables such as judgments, speed or accuracy; that is, outcome measures have been used to infer differences in process. Data on eye-movement patterns would provide critical information on whether the processes actually differ for subjects classified differentially on various dimensions of individual variation. While a few investigators of individual differences have employed eye-movement data, the use of eye-movements has been minimal in an area of obvious applicability.

Eye-movement studies could fruitfully explore the consistency of an individual's cognitive style across various stimulus situations and

over time. The value of a real-time, process-related measure of individual differences is that it may reveal similarities in process even where differences are found in outcome, or vice versa. Thus the use of a process measure indicating what information was collected and when and how it was collected, together with an outcome measure indicating how the information was used may lead to significantly greater precision in differentiations among individuals. The elucidation of these relations would have important consequences for the design of instructional curricula which are sensitive to individual differences in children's styles of learning and for the use of appropriate instructional media. Children with different cognitive styles might be expected to respond differently to picture-text combinations, for example, or to the same material presented in a book or on television.

Cognitive style factors typically have been thought to influence an individual's performance regardless of the nature of the task or of the medium in which the task is presented (e.g., Witkin et al., 1962), but the supporting data are scanty. Pascual-Leone and Goodman (1974), found predictable differences in response to a variety of ambiguous sentences as a function of the reader's cognitive style, and Kagan (1965) found a slight relationship between reflectivity-impulsivity and errors in reading prose. The relations of cognitive style categorizations to performance on a variety of tasks, and to performance on the same task presented in a variety of media, have yet to be finally confirmed or adequately clarified.

Even within the eye-movement behavior itself, differences in individual style are likely to be found. For example Buchsbaum, Pfefferbaum, and Stillman, (1972) reported reliable (over two weeks) individual differences in both eye-movement strategy (content-dependent, task-oriented eye-movements for gathering specific information) and eye-movement style (content-independent features, such as number of fixations per unit of time).

A consideration of the relation between eye-movements and individual difference categories may also clarify data which would otherwise be confounded. If considerable differences in eye-movement patterns exist across individuals, then in randomly selected subject samples these variations will appear as noise and will blur possible structure in the data. An effective way to avoid this noise would be to use cognitive styles and other individual difference variables (e.g., developmental level, learning) as controls in the selection of subjects (cf., Pascual-Leone and Goodman, 1974). The patterns of the data within each sample representative of a particular cognitive style would then be clearer, and the various subject samples could be compared and interpreted in light of the known cognitive styles.

C. PROBLEM SOLVING

RECOMMENDATION: The NIE should support eye-movement research which explores steps in problem solving and variations in those steps as a function of individual or group differences (e.g., age, cognitive style).

In many problem solving tasks it is necessary to acquire visual information at various stages in progress toward problem solution. Eye-movement monitoring of the information acquisition can provide unique, moment-to-moment data on the subject's strategies, and it can do so, given unobtrusive instrumentation, without disrupting his ongoing problem solving attempts.

Eye-movement recording has been used to great advantage in the study of chess strategies (Poznyanskaya and Tikhomirov, 1970; Tikhomirov and Poznyanskaya, 1966) although these studies also caution that the pattern of eye-movements cannot be relied on to mirror thought processes precisely. Eye-movements have also been used to provide information on the processes of anagram solution (Boersma, Muir, Wilton, and Barham, 1969) and of paired-associate learning (McCormack and Moore, 1969). Categorizations of various types of eye-movement patterns and comparisons of the eye-movement patterns of subjects who differ along certain previously specified dimensions (e.g., age, cognitive style) can provide unusually precise, process-related differentiations among approaches to problem solving.

Such information can contribute to the development and testing of models of problem solving. For example, explicit process-structural models of the mental activities of a subject during a task can be (and in some cases have been) developed in accordance with artificial intelligence theories, constructive developmental theories, and psycholinguistic theories. These models can offer step-by-step theoretical descriptions of the mental processes of the subject. If the information required for successive steps in a problem-solving sequence is presented visually, then the eye-movement scan path will provide information on the problem solving strategies of the subject and the theoretical models predictive of the strategies can be tested and refined.

CHAPTER 4

INSTRUMENTATION AND INSTRUMENTALITIES

In the previous sections, we have shown why we believe that eye-movement research is important (and probably critically so) to the understanding of the reading process, picture scanning and television viewing, and to the convergence of several major lines of inquiry and application (i.e., the study of cognitive processes, linguistic communication, and educational psychology) which are starting to affect each other in important ways. Further progress in the intersection of these disciplines requires the close study of moment-by-moment perceptual integration and cognitive analysis. Most theory and practice in the area has rested on eye-movement data that were gathered half a century ago, analyzed and reanalyzed repeatedly as the only body of fact that we have. The techniques by which those data were obtained were highly artificial and constraining, slow to process, and expensive to gather and analyze. The inquiries did not address themselves to issues that have now become critical ones, nor were techniques available to perform the kinds of experiments that we now need (e.g., using the reader's eye-movements themselves to determine what text will meet his gaze when the eye-movement is complete, in order to study the precise nature, role and modifiability of peripherally-guided expectations in the reading process); or using unobtrusive and non-encumbering recording methods that allow us to observe the ways in which children at various levels of development and skill deploy attention when reading or viewing in a normal nonthreatening and unconstrained manner), or the kinds of data-collection, analysis and reduction that modern study, and policy decisions, require.

We need new answers to our new questions, and a new data base for prescribing and assessing instructional procedures. Technological improvements in measuring devices, and in the combination of these devices with small high-speed computers and computer-controlled displays, have provided a major revolution in research potential in this area. We are in a position very much like those of astronomers or virologists who, after decades of theoretical analyses and speculations about what should or might exist, based on indirect and obscure information, face the possibility of obtaining much more direct and abundant evidence about what does in fact exist, by way of space probes and electron microscopes, respectively.

What has probably hindered progress in this area more than anything else over the past generation has been the fact that the equipment and the expertise needed to obtain and apply the relevant information has not been accessible to the researchers whose training and concerns have

been closest to the problem areas. It is now feasible to remedy that situation. In this section, we make several strong and specific recommendations designed to close the gap. At the heart of these recommendations lies revision of NIE's reluctance to support the development of instrumentation and the acquisition of hardware. Although there are good reasons to proceed cautiously in disseminating equipment, and in encouraging the accumulation of hardware, neither expertise, technical facility nor research capacity can be expected in this area of research unless the necessary apparatus and supporting services are available to the users for periods long enough to make the investment worthwhile to them and to the government. This requirement has to be balanced against the needs of economy, especially against the danger of inefficient duty cycles (i.e., of accumulations of instrumental facilities that are underemployed), and some attempts have been made in these recommendations to provide for that balance.

There are four parts to this chapter, relating (I) to research management, review and support, (II) to instrumentation development, (III) to facilities dissemination and establishment, and (IV) to priorities.

RECOMMENDATION: The NIE should develop its own capacity and that of the field to stimulate research in visual information processing.

I. RESEARCH MANAGEMENT, REVIEW AND SUPPORT

RECOMMENDATION: The NIE should establish a study panel to: (1) encourage and evaluate field-initiated research that uses eye-movements (or simulated eye-movements) to study and assess essential skills in reading and comprehension, picture scanning, and television viewing; (2) assign and periodically revise research priorities in the area; and (3) supervise the development and dissemination of needed instrumentation.

A set of relatively specific, but not detailed recommendations as to the kinds of research needed is given in chapter 3. Because knowledge grows unpredictably, and the more valuable ideas and discoveries are often unforeseen in any detailed sense, we have not recommended a program of targeted research. Instead we recommend dissemination of this report to act as a guide for researchers in proposing studies.

We further recommend that a panel be set up to make decisions as to specific research support priorities. That panel should meet as often as financial considerations permit, but no less than once each year, assuming yearly initiation of research grants (less frequently or more frequently depending on this factor). This study panel should be composed of experts from the following areas: (1) education research, particularly reading and television; (2) experimental psychology, particularly visual perception, cognitive processes, and cognitive development; (3) engineering experts in the areas of instrumentation involved. The duties of the panel should be to read new proposals, to assess renewal requests, to assign and revise funding priorities within the area, to advise and consent to the instrumentation needs of specific research proposals, and to oversee the instrumentation development and facilities establishment recommended below. Because of the complexity of the instrumentation involved, and because of the special symbiosis of eye-movement research and instrumentation, the need for engineering expertise in the panel is stressed.

The policy implications of some of the instrumentation recommendations made later in this chapter are sufficiently complex that the study panel will need close and continuing consultation with staff persons from within NIE. Questions, for example, about the suitability of direct grants of public funds to private corporations for instrument development, or about the machinery for appropriate and efficient indirect support for such development, will require careful study. Furthermore, there are serious issues of allocation of funds to the various activities recommended in this chapter and the preceding one. If none of the instrument development proposed in this chapter gets done, that fact will limit research possibilities drastically; if NIE

starves research in order to do the development, however, the problem is even worse. We need some sort of balance that takes into account: (a) the funds available; (b) the state of research, i.e., are we progressing nicely without a massive investment in equipment development, or are we hurting for the new capabilities? (c) the amount of good research proposed; (d) payoff.

Given the high degree of uncertainty about NIE's total budget, and the need for decision about the amount of that total budget to be allocated to eye-movement research and instrumentation, the conference could make no firm recommendations about what the balance should be between the funding of research and the funding of instrument development. Should fiscal exigencies dictate an absolute decision between funding new research using existing instrumentation and funding the development of new instruments, the choice is, of course, clear: presently available equipment is suitable for a variety of new and needed research; and it may be that as demand for improved instruments increases in the field, private companies will undertake the cost of development of the new equipment. Funds will have to be available to researchers to purchase the improved devices, however, or the private sector will not undertake the development risk.

RECOMMENDATION: The NIE should invite and support, and the study panel should oversee, replications of existing studies to determine the extent to which the eye-movement behaviors observed in the original studies are specific to the particular laboratory setting and not representative of normal behavior.

Much of the existing research reviewed by the conference, and much of the proposed research discussed in chapter 3, is concerned with the limits of what people can do, as opposed to what people normally do. For these research purposes instrumentation can be as obtrusive as the researcher requires and as the subject can tolerate. Much essential information has been and will be obtained from studies using, for example, contact lenses and/or fixed retinal image procedures.

On the other hand, a great deal of eye-movement research has been and should be concerned with discovering what people normally do outside the laboratory. Studies that employ eye-movements as indices of cognitive analysis, reading habits or television viewing, for example, have critical relevance for educational practice to the extent that their results can confidently be taken as representative of the normal behavior of the subjects. There may be reason to suspect that in at least some cases the results of previous research studies have been confounded by the subject's knowledge that his eye-movements are of concern to the experimenter or by the physical constraints of the instrumentation used.

The issue of obtrusiveness of instrumentation is of signal importance to the research proposed earlier and most especially to the recommendations for instrument development discussed in the present chapter. If it can be determined that the eye behavior of subjects studied with the relatively obtrusive equipment currently available is truly representative of their normal behavior, then at least one expensive development activity recommended below (section III.C) can be dispensed with, and future research can build with confidence on the foundation established by previous studies. If, on the other hand, it is found that eye behavior is different when unobtrusive equipment is used, then some earlier conclusions reached on the basis of obtrusively acquired data will have to be re-examined, future research studies using similarly obtrusive equipment will need to be cautious in their analyses of data, and relatively higher priority must be given to the development of less obtrusive instrumentation. Given the importance of the issues involved, these replication studies should be undertaken as soon as possible; and decisions about some of the instrumentation recommendations made below should await the results.

II. INSTRUMENTATION DEVELOPMENT

RECOMMENDATION: The NIE should invite and support specific research and development of instrumentation to improve the ease, efficiency and validity of eye-movement research. This research and development should be addressed both to the development of new instruments and to the improvement of existing instruments.

A. RECOMMENDATIONS FOR DEVELOPMENT OF NEW INSTRUMENTS

The following suggestions for new instrumentation are not listed in order of priority. The study panel recommended in section I should, as one of its first tasks, consider these and other suggestions for new instruments and assess their suitability for presently conceived research, and the future need for them as best as the panel can foresee it.

(1) Two or three independent feasibility studies, costing approximately $5,000.00 apiece, should be invited to determine whether it would be possible to produce devices contained in what amounts to a hard-page book binder (or other similar arrangement that permits the reader to hold in his hand the reading matter on which his eye-movements are to be observed) which would allow the measurement of eye fixation from the frame of reference of the book itself. The purpose of such a device would be to permit subjects to engage in reading behavior closer to their normal behavior than is permitted by other less flexible eye-monitoring devices. The recommended instrument should be capable of $1^{\circ} - 2^{\circ}$ resolution, and should require little or no special cooperation from the subject, although a light-weight head marker to establish a head reference may be acceptable.

Temporal resolution should be possible to within 100 msec., and output should be an electrical signal readily stored and accessible to computer analysis. If the feasibility studies indicate that such devices can be made available at costs within the range of the second category described in (B) below in quantities that are within the range that are likely to be requested and employed by research workers in the field, NIE should undertake to develop the device and publicize its availability.

(2) Develop an unobtrusive and covert eye-movement measurement instrument that is integrated within a console structure, such as a microfiche reader, which may be placed in a normal library setting. This would have to work with minimum or no subject cooperation. This device should be capable of $1/2^{\circ}$ spatial resolution and 1° accuracy, and a temporal resolution of 60 Hz.

(3) Encourage the development of a practical method for recording voice and fixations conjointly in an eye-voice span instrument. The voice record should be amenable to analysis and summary in the output format described in item (II, B, 8), below, as an indicator showing the time of utterance of each word relative to the fixation point then being made.

B. RECOMMENDATIONS FOR IMPROVEMENT OF EXISTING INSTRUMENTATION

Besides the improvement in performance specifications which is desirable in new instrumentation development, there is a consensus among users of existing instrumentation about the need for "more comfortable" equipment, not only from the subject's point of view but from the user's as well. It should incorporate reliability with ease of use and be as amenable as possible to automated data processing. More specific recommendations are as follows:

(1) Extend the head movement freedom of eyetracking instruments that use the double Purkinje image method to accommodate a couple of inches of motion. This is very important in connection with measuring the eye-movements of children, and permitting them to speak, unencumbered by a bite-board. A direct development contract might be solicited and issued for this purpose.

(2) Increase the accuracy of the instruments that measure the separation between the corneal reflection and the pupil center to the $1/4^{\circ}$ - $1/2^{\circ}$ of accuracy of which they appear to be capable in principle.

(3) Increase the speed of response of the television-based eye-movement monitoring methods to 120 samples/second or more.

(4) Develop general purpose off-line electronic systems for analysis of film or video tape frames obtained from any of the existing and widely available corneal reflex cameras. At the same time, investigate the possibility of image-enhancement techniques applied to photographic records that may suffer from graininess, or other quality problems, to make them more useful for extraction of data. These procedures should automatically extract eye position coordinates, as described in item 8 below, and would increase the utility of many presently owned systems and make their use vastly more efficient and compatible with those obtained by more sophisticated methods. A feasibility study, for less than $5,000, should be solicited from one of the existing government facilities currently engaged with image-processing technology and, if the service appears to be a possible one to offer, it should be publicized in the notifications that NIE will entertain field initiated research.

(5) Develop an integrated electrode-amplifier combination for use in electro-oculography. This would reduce the noise susceptibility

problems, eliminate some of the psychological difficulties that are provided by trailing shielded wires, and broaden the utility of this method.

(6) Develop accommodation measurement capability to be integrated with eye position measurements to determine where the eye is focused at any point. This would effectively give the three-axis measure of eye position. This parameter may be an important one in determining states of attention and vigilance. Stanford Research Institute has been developing such a device, although it has yet to be coupled with their eye-tracker. It seems appropriate that further development of the SRI device be encouraged, and perhaps funded, and that pilot studies using three-axis measurement be undertaken to determine whether this more elaborate instrumentation is indeed useful to the field and for what purposes.

(7) Develop a self-calibration method for one of the unobtrusive free-head point-of-regard systems which would allow the system to be calibrated without requiring subject cooperation.

(8) Develop a method and format of recording reading fixation patterns in a manner comparable to Buswell's (1935). A desired output would be a copy of the presented material on which is superimposed the pattern of fixation points; the temporal order of those points; and the durations of the fixations.

III. FACILITIES DISSEMINATION AND ESTABLISHMENT

RECOMMENDATION: The NIE should support, and the study panel should oversee, the dissemination of eye-movement instruments and related technology, and the establishment of facilities which increase the ease, accessibility and efficiency of eye-movement research on reading, the scanning of pictures and graphic displays and television viewing.

The need for wider dissemination of eye-movement instruments and their related technologies has been discussed earlier in this chapter. This section will discuss the various types of instruments and the kinds of facilities and supporting services necessary to advance the eye-movement research recommended in chapter 3.

In reviewing the recommended research that was presented to the conference, it was clear that most of the research can be done with existing equipment, or with relatively slight improvements in existing equipment. It also became clear that there are three categories of research equipment required, and different courses of action are needed to encourage the equally worthy and important research in each of these categories.

A. INSTRUMENTS OF MODERATE ACCURACY AND RESOLUTION

A strong case can be made for the view that, except for special experiments, instrumentation requirements are for the most part not particularly stringent and can usually be met by relatively modest equipment.

To put requirements into a broad perspective, discrimination of 1^{o} of eye-movement is sufficient for one word resolution, which is more than is required by many experiments and is certainly sufficient for a great number. Saccades occur with an average rate of 4 per second, and therefore temporal resolution need only be sufficient for samples of about 10 per second. There is a large category of head-mounted equipment (corneal reflection, EOG, iris-scleral reflection, etc.) which is limited by the stability of the eye within the head. There is some evidence (Cornsweet and Crane, 1973) to indicate that there is eyeball translation within the head of up to 1 mm (this is equivalent to eye rotation of 1^{o}). This will probably still be within the acceptable tolerance for coarse reading studies, but the researcher should be aware of this potential source of error. Not all of the highest performance criteria of the various instruments available are needed to produce useful research results. Clearly, some parameters

are more important than others, and the best possible system that meets the minimum requirements can be chosen and employed. As an example, a researcher may not be interested in, nor need to detect, fine eye-movements; he may not need to look at the high-frequency details of a saccade; or his range requirements may be small. He may therefore be satisfied with a simpler, less powerful instrument. (See Appendix, especially Table 6.1, for the characteristics of the various available eye-movement measurement instruments.)

As the Mackworths pointed out during the conference, encouragement of research with such equipment would be relatively economical and would repay us with a great deal of data -- if suitable precautions were observed. Encouragement could be provided by publishing information about the equipment (and sources) available for different levels of research requirement, by providing accurate descriptions of the measurement characteristics of the instruments and of the standardized conditions to which those descriptions apply, and the research, diagnosis and training limitations appropriate to each kind of instrument. Equipment itself could be made available as part of research grants of modest size, equipment to reside with the institution with which the research is being done, in order to encourage the institution and the researchers to invest the time in learning how to use the equipment; or both training and loan of the instruments could be obtained from a center (see below) in which instruments might be located for distribution as needed -- a sort of lending library of equipment. Perhaps a questionnaire, and an in-house study of the relative costs involved, would establish which of these alternatives is cheaper and more desirable.

Inexpensive equipment can still be prohibitively expensive if it generates unusable research. A set of precautions on research requirements -- of a methodological, procedural and sampling nature -- should be included with invitations for field-initiated research in this area, and the fact that the study panel will have to be satisfied on matters of experimental design and purpose of inquiry should be made clear to prospective applicants. Availability of the data for reanalysis by subsequent investigators is of particular importance. The experimenter should pay sufficient attention to the handling and analysis of the data produced by the eye-movement measurement instrumentation. Processing the raw eye-movement data can be made easier by the use of digital computers. The users of inexpensive equipment are the most likely, in general, to need assistance in this matter, and the research community as a whole would benefit from a central collection of data processing aids. These could range from general flow chart procedures, to user language programs, to computer tapes directly usable on the researcher's computer.

If this approach becomes generally acceptable, the output data also becomes more compatible for use by many different experimenters and can form the basis of an archival source. Computer-produced reading-fixation patterns of the type generated by Buswell (1935) are generally agreed to be one useful such format (item II, B, 8, above).

B. INSTRUMENTS OF HIGH ACCURACY AND RESOLUTION, AND OF INTERMEDIATE COST

There are many purposes to which Class A instruments are inadequate. Greater accuracy and resolution, greater speed of processing, greater subject freedom, etc., may be needed in varying combinations. A major need is for devices that permit the experimenter to change the display while the subject moves his eye (in ways that are contingent on the eye-movement) in order to study, and perhaps to train, the process of retrieving information, glance by glance. The resolution and accuracy of the device depends on the question being asked; if resolution of a single character is needed, $1/4^{\circ}$ of spatial resolution and accuracy of measurement will suffice. Sampling of eye position must be of the order of 10 msec., and the output must be a signal acceptable to a computer, if on-line monitoring of the signal is to be maintained. More or less precision and accuracy can be achieved by means of different devices, each having their own advantages and disadvantages. Some fundamental questions require very high precision, accuracy and resolution: e.g., the variation in acuity as a function of distance from the center of the fovea is apparently not simple, nor clearly understood. Experiments have shown that under "dynamic" conditions peripheral acuity can be quite high. In any case, a great deal of visual information can be obtained from regions outside of the fovea. Research is called for on these problems that are fundamental to the reading process. Presently, only tight-fitting contact lenses can be used to get the necessary precision, but new instruments (and particularly the first-fourth Purkinje-reflection device) appears to have removed that restriction and, perhaps, made the question one that can be explored at different ages. Increasing instrument speed (a bandwidth of over 200 Hz is now possible) makes possible exploration of the temporal details of saccades themselves. There is some reason to believe that their time course may provide sensitive indications of such variables as arousal and emotion. To another point, it may also be possible to have the computer predict the landing point of a saccade from the initial rise time of the eye's angular speed, a refinement which McConkie's research is now pressing.

The instrumentation that we are discussing here must be fitted closely to the individual experimenter's need, and it must evolve to meet the conditions of the research. Instruments of this type are in general moderately expensive ($15,000 and higher for recording instruments, and approximately $20,000 for computers and associated equipment.) They characteristically require relatively high levels of expertise for operation and maintenance. While wide dissemination of

these instruments is neither practical nor desirable, it may be possible to increase access to such equipment, and to improve the efficiency of its use by making instruction in its use, software, adapting hardware, and even exchange facilities (e.g., trades, loans and rentals) generally available and by publicizing this availability.

In general, encouragement of this level of instrumentation can probably best be achieved by supporting research requests that include such equipment as part of the budget, and making sure that the specifications of the equipment are appropriate to the research questions being asked. Present policy of requiring equipment to be returned as soon as the research is completed is certain to be ill-advised: researchers in this field normally invest a great deal of time and money gaining expertise in the equipment, in adapting it to their specific research needs, and in acquiring supporting equipment and programs that are particularly adapted to form a usable system. All of this may be lost if the investigator pauses in his inquiry, for reasons having nothing to do with either the merit of his plans or with his long term goals, and a central part of the system is reclaimed at that time. Where this procedure has been imposed it should certainly be abandoned.[1] On the other hand, it may be possible to make research installations of this sort available, on a time-sharing basis, to other researchers who are only starting in the area, or who do not have long-term commitments to research with the individual system in question. It would be possible to make agreements to this effect part of the conditions of funding the acquisition of the installation and to publicize the availability of the service. When an investigator leaves the field of research for any substantial period (e.g., several years), or permanently, the equipment should then be reclaimed and its availability for research should be publicized.

This issue is probably not of major economic importance at this level of instrumentation, because there will not be a great number of researchers working at this level. It is at levels A and C that the instrument sharing becomes important, and at level C, which we discuss below, it is essential.

C. CENTRAL FACILITIES FOR EXPENSIVE EQUIPMENT AND SERVICES

It is often desirable to keep the eye-movement measurement situation as close to the natural reading or viewing situation as possible, and to avoid the atmosphere of a laboratory test. (We have discussed

---

[1]NIE will consider requests to allow specialized scientific equipment to remain on site after the termination of a grant.

the importance of this consideration in amplifying on the recommendation in section I that replications of previous studies be done using unobtrusive instruments.) Moreover, in testing children, a system must be used which requires minimal subject training or cooperation. This often precludes the use of contact lens methods or even EOG under some experimental conditions, and an instrument which can be set up quickly with minimum calibration is needed. In the extreme case, we need an instrument of which the subject may in fact be completely unaware (although of course informed consent of legal guardians, and full disclosure after the experimental session, are both desirable and necessary).

A combination of high precision ($1/4^o - 1/2^o$), high speed, rapid online data analysis, and highly unobtrusive measurement conditions is extremely expensive to achieve, and requires expert maintenance. At the present state of the art, one such installation already exists at the U.S. Army Human Engineering Laboratory at Aberdeen Proving Grounds, Maryland, and this could provide a center that could provide research services to scientists on visiting grants of varying duration. It meets almost all the desired requirements, but needs further development. We have already recommended (II, B, 2) that equipment that works on this principle (measurement of the separation between corneal reflection and pupil center) be brought to the $1/4^o$ or $1/2^o$ accuracy and precision of which it is theoretically capable. The HEL installation is the only one of its kind that is also almost totally unobtrusive. (Considering its expense, it is unlikely that another will be built.) In addition, NIE should explore whether the Aberdeen installation is an efficient and convenient locus for several other services which should be centralized for the purposes of increasing the efficiency and utility of research using eye-movement measures in reading, television viewing and cognitive processing, or whether it should be moved. We discuss these other services below as if they were to be provided at a central institution, but it is obviously not essential that they all be centralized at the same installation:

(1) Central Visual Data Retrieval and Processing. The various forms of eye-movement photography have the advantages of relative simplicity of technology and economy of equipment. The records are expensive, however, and laborious to read with precision, and the task of automating retrieval of the data from such records is technically difficult and highly expensive. It is probably the case, however, that the use of image-enhancement techniques that are now available would increase the precision of the information that such films could yield (especially in the case of relatively grainy high-speed infrared records), and it is also probably the case that automated data retrieval facilities now in existence could be made available at a center. These services would improve the efficiency of operation and the precision of a wide range of devices (especially of the type discussed in A, above) that are used in individual laboratories and institutions around the country, as long as those uses did not require rapid data analysis,

(d) Software programs which generate pictorial format, 2-dimensional representation of the eye-movement pattern. These would require computer plotters, graphic displays, or other such devices.

The compiled information should be as detailed as possible to permit conversion by a user to his own system when necessary. This service should probably be the responsibility of the same person(s) entrusted with the literature survey, discussed below.

(3) Literature Survey. There is no central journal devoted to eye-movement measurement (and there is certainly none devoted to eye-movement measures in the service of research on reading picture scanning and television viewing); nor is it desirable to have one -- the researchers come at the problem from too many disparate fields, and this will probably continue to be the case. But a continual updating of the literature would be extremely worthwhile and probably quite inexpensive (in part, it could be a requirement of research undertakings supported by NIE grants), and it would be an appropriate activity for personnel at a facilities center to undertake. Such a survey would be a necessity if the study panel were to work effectively. It would be even more necessary if the evaluation panel (section I), set up to review accomplishments after a five year period, were to be able to obtain a coherent view of the field without a prohibitive investment of time. The literature survey should probably be directly contracted by NIE, and periodically supervised by the study section panel.

(4) Equipment "Library." In order to ensure that eye-movement recording equipment is used as continuously as possible, and to provide a starting basis for researchers to perform pilot experiments, the center should keep a collection of simple, mobile conventional instruments (of the type discussed in III, A, above, and perhaps some instruments described in III, B) which may be loaned to other institutions to simplify their instrumentation needs and to make NIE sponsored research more economical. An instrument repertory for psychophysiological measures related to eye-movements should also be accumulated. These should include EEG, heart rate, GSR, breath rate, EMG, etc. With such a pool in existence, it would be possible for researchers whose interests bring them to eye-movement research only occasionally to undertake that research without prohibitive investment in equipment and space, and it would become sensible for NIE to pursue, at least in part, its policy of retrieving equipment when it is not being used for active research.

IV. PRIORITIES

We recommend that resources be allocated with the following priorities in order that planned research may proceed in the most efficient fashion:

(1) Establishment of a Study Panel. (See section I, pages 4-3 and 4-4.) In addition to the responsibilities described above, the panel should review this list of priorities in light of NIE's level of funding.

(2) Wide Dissemination of Relatively Inexpensive Instrumentation. (See pages 4-1 and 4-2, and section III.A) Reasonably priced and efficient instrumentation must be made available to researchers in order that research horizons not be limited by inadequate equipment or none at all. Wide availability of eye-movement instrumentation is likely to attract to the field a variety of researchers who would otherwise turn to other, less suitable research methods. It is also considered important that instrumentation obtained by researchers on NIE grants not have to be dismantled and returned to NIE at the conclusion of the project for which it was acquired. This is clearly disruptive of the continui: · necessary if planned programs of research are to be undertaken.

(3) Replication Studies to Determine the Need for Unobtrusive Instruments. (See section I, pages 4-4 and 4-5.) NIE should fund or encourage the undertaking of tests at a facility such as the Human Engineering Laboratory at Aberdeen Proving Ground to determine if unobtrusive eye-movement recording will result in data different from that obtained using other more encumbering methods.

(4) Improvements in Existing Instrumentation. (See section II.B, pages 4-7 and 4-8.) NIE should fund or encourage the instrument improvements described.

(5) Development of New Instruments. (See section II.A, pages 4-6 and 4-7.) To the degree possible, given the level of future funding of NIE and the allocation of NIE funds to eye-movement research, the study panel should guide the development of new instrumentation to be funded or encouraged by NIE, including some or all of the instruments described.

(6) Establishment of a Central Research Facility. (See section III.C, pages 4-12 to 4-15.) NIE should fund or encourage the long-range development of a central research facility with the various capabilities as described. The expensive equipment specified for

inclusion in such a center should be developed or acquired as pressing need for such equipment arises in the field. Feasibility studies should be undertaken as soon as possible, however, to determine the extent of present needs that may exist, to estimate as accurately as possible the equipment specifications necessary to meet future needs, to determine a time schedule for the future development of such equipment, and to determine the cost. The supporting services which we have recommended be supplied by such a central research facility need not be approached with the same caution. The image-enhancement and automated-data-retrieval services, the compilation and dissemination of software and data processing aids and programs, and the literature survey all would contribute substantially to improving the quality and efficiency of eye-movement research, and should receive higher priority treatment than their mention here would suggest. Similarly, the equipment "lending library" should be considered as a supplement to, not a replacement for, the dissemination of instrumentation urged in priority (2) above.

REFERENCES

Abrams, S.G., and Zuber, B.L. Some temporal characteristics of information processing during reading. Reading Research Quarterly, 1972, 8, 42-51.

Adler, F.H. Physiology of the eye. (4th ed). St. Louis: C.U. Mosby, 1965.

Ahlwat, K. Evaluation of the effects of differential modes of television presentation on children's looking time. Unpublished Masters thesis, Ontario Institute for Studies in Education, 1970.

Antes, J.R. The time course of picture viewing. Journal of Experimental Psychology. 1974, 103, 162-170.

Ault, R.L., Crawford, D.E., and Jeffrey, W.E. Visual scanning strategies of reflective, impulsive, fast-accurate, and slow-inaccurate children on the Matching Familiar Figures test. Child Development, 1972, 43, 1412-1417.

Ball, S., and Bogatz, G.A. Reading with television: An evaluation of "The Electric Company." Princeton, New Jersey: Educational Testing Service, 1973.

Benton, C. Comment: The eye and learning disabilities. Journal of Learning Disabilities, 1973, 6 (5), 66-68.

Boersma, F.J.. Muir, W., Wilton, K., and Barham, R. Eye movements during anagram tasks. Perceptual and Motor Skills, 1969, 29 (2), 371-374.

Bouma, H. and DeVoogol, A.H. On the control of eye saccades in reading. Vision Research, 1974, 14, 271-272.

Briggs, J. Reading, eye movements and instructional television. Unpublished Doctoral dissertation, Ontario Institute for Studies in Education, 1973.

Buchsbaum, M., Pfefferbaum, A., and Stillman, R. Individual differences in eye-movement patterns. Perceptual and Motor Skills, 1972, 35, 895-901.

Buswell, G.T. How people look at pictures. Chicago: University Press, 1935.

Carpenter, P.A., and Just, M.A. Semantic control of eye movements during picture scanning in a sentence-picture verification task. Perception and Psychophysics, 1972, 12, 61-64.

Cohen, K.M. Eye movements and the development of psychological processes. Paper submitted to the NIE Conference on Eye Movement Research and Technology, June, 1974.

Comunale, A.S. Visual selectivity in reading: A study of the relationship between eye movements and linguistic structure. Unpublished Doctoral dissertation, School of Education, University of Massachusetts, 1973.

Conklin, R.C., Muir, W., and Boersma, F.J. Field-dependency-independency and eye movement patterns. Perceptual and Motor Skills, 1968, 26, 59-65.

Cooper, R.M. The control of eye fixation by the meaning of spoken language. Cognitive Psychology, 1974, 6, 84-107.

Cornsweet, T.N., and Crane, H.D. Accurate two-dimensional eye tracker using first and fourth Purkinje images. Journal of the Optical Society of America, 1973, 63, 921.

Day, M.C. Developmental trends in visual scanning. Unpublished Qualifying Paper, Harvard Graduate School of Education, 1974.

DeVries, R.E. Evaluation of the effects of differential techniques of television presentation on children's performance on concrete versus abstract and familiar versus unfamiliar concept tasks. Unpublished Master's thesis. Ontario Institute for Studies in Education, 1970.

Drake, D.M. Perceptual correlates of impulsive and reflective behavior. Developmental Psychology, 1970, 2, 202-214.

Easterbrook, J.A. The effect of emotion on cue utilization and the organization of behavior. Psychological Review, 1959, 66, 183-201.

Engel, F.L. Visual conspicuity, directed attention and retinal locus. Vision Research, 1971, 11, 563-576.

Flax, N. The eye and learning disabilities. Journal of Learning Disabilities, 1973, 6 (5), 60-64.

Fowles, B. A pilot study of verbal report in formative research in television. Unpublished Doctoral dissertation, Yeshiva University, 1973.

Fraisse, P., Ehrlich, S., and Vurpillot, E. Etudes de la centration perceptif par la methode tachistoscopique. Archives de Psychologie Geneve, 1956, 35, 193-214.

Gardner, R.W., and Schoen, R.A. Differentiation and abstraction in concept formation. Psychological Monographs, 1962, 76 (41, Whole No. 560).

Geyer, J.J. Perceptual systems in reading. On H. Singer and R.B. Ruddell (eds.), Perception and Reading. Newark, Delaware: International Reading Association, 1963.

Geyer, J.J. Perceptual systems in reading: A temporal eye-voice span constant. Unpublished Doctoral dissertation, University of California, Berkeley, 1966.

Geyer, J.J. Comprehensive and partial models related to the reading process. Reading Research Quarterly, 1972, 7, 541-587.

Gibbon, S.Y., and Palmer, E.L. Pre-Reading on "Sesame Street." New York: Children's Television Workshop, 1970

Gibbon, S.Y., Palmer, E.L., Fowles, B. "Sesame Street," "The Electric Company" and reading. In J.B. Carroll and J.S. Chall (eds.), Toward a Literate Society. New York: McGraw-Hill, in press.

Gibson, E.J., Pick, A.D., Osser, H., and Hammond, M. The role of graphics-phonemes correspondence in the perception of words. American Journal of Psychology, 1962, 75, 554-570.

Gilbert, L.C. Functional motor efficiency of the eyes and its relation to reading. University of California Publications in Education. Berkeley: University of California, 1953, 11 (3), 159-232.

Glaser, R. Individuals and learning: The new aptitudes. Educational Researcher, 1972, 5-13.

Gollin, E.S. Tactual form discrimination: Developmental differences in the effects of training under conditions of spatial interference. Journal of Psychology, 1961, 51, 131-140.

Goodman, K.S. Reading: A psycholinguistic guessing game. In H. Singer and R.B. Ruddell, (eds.), Theoretical Models and Processes of Reading. Newark, Delaware: International Reading Association, 1970.

Gould, J.D. Eye movements during visual search and memory search. Journal of Experimental Psychology, 1973, 98, 184-195.

Grindley, G.C., and Townsend, V. Voluntary attention in peripheral vision and its effects on acuity and differential thresholds. Quarterly Journal of Experimental Psychology, 1968, 20, 11-19.

Guthrie, J.T. Models of reading and reading disability. Journal of Educational Psychology, 1973, 65 (1), 9-18.

Haber, R.N., and Hershenson, M. The psychology of visual perception. New York: Holt, Rinehart and Winston, 1973.

Haith, M.M. Infrared television recording and measurement of ocular behavior in the human infant. American Psychologist, 1969, 24 (3), 279-283.

Hale, G.A., and Morgan, J.S. Developmental trends in children's component selection. Journal of Experimental Psychology. 1973, 15, 302-314.

Hall, R.J., Rosenberger, M.A., and Monty, R.A. An experimental investigation of the visual behavior of young heroin addicts and matched controls. JSAS Catalog of Selected Documents in Psychology, 1974, 4, 7.

Havens, L.L., and Foote, W.E. Structural features of competitive responses. Perceptual and Motor Skills, 1964, 19, 75-80.

Hebb, D.O. Semiautonomous process: Its nature and nurture. American Journal of Psychology, 1963, 18, 16-27.

Helmholtz, H.V. In J.P.C. Southall (Ed.), Physiological optics, (Vol. 3). New York: Optical Society of America, 1925.

Hochberg, J. Attention, organization, and consciousness. In D.I. Mostofsky (Ed.). Attention: Contemporary theory and analysis. New York: Appleton-Century-Crofts, 1970(a).

Hochberg, J. Components of literacy: Speculations and exploratory research. In H. Levin and J.P. Williams (Eds.), Basic Studies on Reading. New York: Basic Books, 1970(b).

Hochberg, J., and Brooks, V. Pictorial recognition as an unlearned ability: A study of one child's performance. American Journal of Psychology, 1962, 75, 624-628.

Hochberg, J., and Brooks, V. The perception of television displays. New York: The Educational Television Laboratory of the Educational Broadcasting Corporation, 1973.

Jeffrey, W.E. The orienting reflex and attention in cognitive development. Psychological Review, 1968, 75, 323-334.

Just, M.A., and Carpenter, P.A. Comprehension of negation with quantification. Journal of Verbal Learning and Verbal Behavior, 1971, 10, 244-253.

Kagan, J. Reflection-impulsivity and reading ability in primary grade children. Child Development, 1965, 36, 609-628.

Kagan, J., and Kogan, N. Individuality and cognitive performance. In P.H. Mussen (Ed.), Manual of Child Psychology. New York: Wiley, 1970.

Kahneman, D. Attention and effort. Englewood Cliffs, New Jersey: Prentice-Hall, 1973.

Keeley, S.M. Visual detection as a function of attentional demand and perceptual system error. Perception and Psychophysics, 1969, 6, 73-77.

Kennedy, J.M. Regressive eye movements may depend on syntax. Unpublished manuscript, Cornell University, 1967.

Kerr, J.L. Visual resolution in the periphery. Perception and Psychophysics, 1971, 9, 375-378.

Kolers, P.A. Reading and talking bilingually. American Journal of Psychology, 1966, 79, 357-376.

Kolers, P.A. Three stages of reading. In H. Levin and J.P. Williams (Eds), Basic Studies on Reading. New York: Basic Books, 1970.

Kolers, P.A. The recognition of geometrically transformed text. Perception and Psychophysics, 1968, 3, 57-64.

Kolers, P.A. Experiments in reading. Scientific American, 1972, 227, 84-91.

LaBerge, D., and Samuels, S.J. Toward a theory of automatic information processing in reading. Cognitive Psychology, 1974, 6, 293-323.

Lakowski, R., and Aspinall, P. Static perimetry in young children. Vision Research, 1969, 9, 305-312.

Lambert, W.E. Language, psychology, and culture. Stanford, California: Stanford University Press, 1972.

Lambert, W.E., and D'Anglejan, A. The cognitive, linguistic, and attitudinal consequences of elementary education in a second language. Paper presented at the annual meeting of the International Reading Association, Denver, 1973.

Lesser, G.S. Children and television: Lessons from Sesame Street. New York: Random House, 1974.

Levin, H., and Kaplan, E. Eye-voice span (EVS) within active and passive sentences. Language and Speech, 1968, 11, 251-258.

Liebert, R.M., Neale, J.M., and Davidson, E.S. The early window: Effects of television on children and youth. New York: Pergamon Press, 1973.

McConkie, G.W., and Rayner, K. The span of the effective stimulus during fixations in reading. Paper presented at the American Educational Research Association meetings, New Orleans, 1973(a).

McConkie, G.W., and Rayner, K. The perceptual span in reading. Final report submitted to the U.S.O.E., 1973(b).

McCormack, P.D., and Moore, T.E. Monitoring eye movements during the learning of low-high and high-low meaningfulness paired-associate lists. Journal of Experimental Psychology, 1969, 79.

McGuigan, F.J. The function of covert oral behavior ("Silent Speech") during silent reading. International Journal of Psycholinguistics, in press.

McGuigan, F.G., and Bailey, S. Logitudinal study of covert oral behavior during silent reading. Perceptual and Motor Skills, 1969, 28 (1), 170.

McGuigan, F.J., Keller, B., and Stanton, E. Covert language responses during silent reading. Journal of Educational Psychology, 1964 55, 339-343.

McGuigan, F.J., and Pinkney, K.B. Effects of increased reading rate on covert processes. Interamerican Journal of Psychology, in press.

McGuigan, F.J., and Rodier, W.I. Effects of auditory stimulation on covert oral behavior during silent reading. Journal of Experimental Psychology, 1968, 76, 649-655.

McGuigan, F.G., and Shepperson, M.H. The effect of remedial reading on covert oral behavior. Journal of Clinical Psychology, 1971, 27, 541-543.

McLuhan, M Understanding media: Extensions of man. New York: McGraw-Hill Book Co., 1964.

Mackworth, N.H. Visual noise causes tunnel vision. Psychonomic Science, 1965, 3, 67-68.

Mackworth, J.F. Some models of the reading process: Learners and skilled readers. Reading Research Quarterly, 1972, 7, 701-731.

Mackworth, N.H., and Morandi, A.J. The gaze selects informative details within pictures. Perception and Psychophysics, 1967, 2, 547-551.

Macnamara, J., Feltin, M., Hew, M., and Klein, M. An analytic comparison of reading in two languages. Irish Journal of Education, 1968, 2 (1), 41-53.

Marchbanks, G., and Levin, H. Cues by which children recognize words. Journal of Educational Psychology, 1965, 56, 57-61.

Mehler, J., Bever, T.G., and Carey, P. What we look at when we read. Perception and Psychophysics, 1967, 2, 213-218.

Miller, L.K. Eye-movement latency as a function of age, stimulus uncertainty, and position in the visual field. Perceptual and Motor Skills, 1969, 28, 631-636.

Mock, K. The relationship of audiovisual attention factors and reading ability to children's television viewing strategy. Unpublished paper, Ontario Institute for Studies in Education, 1974.

Neisser, U. Cognitive psychology. New York: Academic Press, 1967.

Neisser, U. Selective reading: A method for the study of visual attention. Paper presented to the 19th International Congress of Psychology, London, 1969.

Noton, D., and Stark, L. Eye movements and visual perception. Scientific American, 1971, 224 (6), 33-43.

O'Bryan, K.G. Eye-movement research and the development of educational technology in programmes for the slow reader. Unpublished report, Ontario Institute for Studies in Education, 1975.

O'Bryan, K.G., and Boersma, F.J. Eye movements, perceptual activity, and conservation development. Journal of Experimental Child Psychology, 1971, 12, 157.

O'Bryan, K., and Silverman, H. Report on children's viewing. Unpublished manuscript, Ontario Institute for Studies in Education, 1973.

Paivio, A. Imagery and verbal processes. New York: Holt, Rinehart and Winston, 1971.

Palmer, E.L. Formative research in educational television production: The experience of the Children's Television Workshop. In W. Schramm (ed.), Quality in Instructional Television. Honolulu: University Press of Hawaii, 1972.

Pascual-Leone, J. A mathematical model for the transition rule in Piaget's developmental stages. Acta Psychologica, 1970, 32, 301-345.

Pascual-Leone, J. A theory of constructive operators. A neo-Piagetian model of conservation and the problem of horizontal decolage. Final report, grant NRC APA 0234, 1973.

Pascual-Leone, J., and Goodman, D. Cognitive style factors in linguistic performance. Paper presented at the Canadian Psychological Association Annual Meeting, Windsor, 1974.

Peckham, R.H. Visual discrimination in pre-school children. Child Development, 1933, 4, 292-297.

Piaget, J. The mechanisms of perception. Trans. by G.N. Seagrim. London: Routledge and Kegan Paul, 1969.

Poznyanskaya, E.D., and Tikhomirov, O.K. On the functions of eye movements. Soviet Psychology, 1970, 8 (3-4), 172-178.

Rayner, K. The perceptual span and peripheral cues in reading. Research Report No. 2, Dept. of Education, Cornell University, 1974.

Rovet, J. Can spatial skills be applied via film? Analysis of the cognitive consequences of visual media. Unpublished Doctoral dissertation, Ontario Institute for Studies in Education, 1974.

Rust, L.W. Attributes of the "Electric Company" pilot shows that produced high and low visual attention in 2nd and 3rd graders. CTW Research Department, 1971.

Salomon, G. Can we affect cognitive skills through visual media? An hypothesis and initial findings. Audio-Visual Communication Review, 1972, 20, 401-422.

Sanders, A.F. The selective process in the functional visual field. Monograph from Institute for Perception, National Defense Research Organization TNO. Soesterberg, The Netherlands, 1963.

Santostefano, S.G. A developmental study of the cognitive control "leveling-sharpening." Merrill-Palmer Quarterly, 1964, 10, 343-360 (a).

Santostefano, S.G. Cognitive controls and exceptional states in children. Journal of Clinical Psychology, 1964, 20, 213-218 (b).

Sperling, G. The information available in brief visual presentations. Psychological Monographs, 1960, 74, (whole No. 498).

Taylor, E.A. Controlled reading. Chicago: University of Chicago Press, 1937.

Taylor, E.A. The spans: Perception, apprehension, recognition. American Journal of Ophthalmology, 1957, 44, 501-507.

Taylor, S.E. Eye movements in reading: Facts and fallacies. American Education Research Journal, 1965, 2, 187-202.

Tikhomirov, O.K., and Poznyanskaya, E.D. An investigation of visual search as a means of analyzing heuristics. Soviet Psychology, 1966-67, 5 (2), 3-16.

Tinker, M.A. Recent studies of eye movements in reading. Psychological Bulletin, 1958, 55, 215-231.

Tinker, M.A. Bases for effective reading. Minneapolis: University of Minnesota Press, 1965.

Venger, L.A. Selections from Perception and learning Soviety Psychology, 1971, 10, 5-108.

Volkman, F.C. Vision during voluntary saccadic eye movements. Journal of the Optical Society of America, 1962, 52, 571-578.

Volkman, F.C., Schick, A.M.L., and Riggs, L.A. Time course of visual inhibition during voluntary saccades. Journal of the Optical Society of America, 1968, 58, 362-369.

Vurpillot, E. The development of scanning strategies and their relation to visual differentiation. Journal of Experimental Child Psychology, 1968, 6, 632-656.

Wanat, S.F. Linguistic Structure and Visual Attention in Reading. Unpublished Doctoral dissertation, Cornell University, 1971.

Wanat, S.F. Structural predictability and overt scanning behaviors. Paper presented at the Annual Meeting of Eastern Psychological Association, Boston, 1972.

Willows, D.M. Reading between the lines: Selective attention in good and poor readers. Unpublished manuscript, 1974.

Witkin, H.A., Dyk, R.B., Faterson, H.F., Goodenough, D.R., and Karp, S.A. Psychological differentiation. New York: Wiley, 1962.

Wohlewill, J.F. Developmental Studies of perception. Psychological Bulletin, 1960, 57, 249-288.

Wolf, W. Perception of visual displays. Viewpoints: Bulletin of the School of Education, Indiana University, 1971, 47, 112-140.

Woodworth, R.S. Experimental Psychology. New York: Holt, 1938.

Woodworth, R.S., and Schlosberg, H. Experimental Psychology. New York: Holt, Rinehart & Winston, 1954.

Zachrisson, B. Studies in the legibility of printed text. Stockholm: Almquist & Wiksell, 1965.

Zaporozhets, A.V. The development of perception in the pre-school child. In P. Mussen (ed.) European Research in Child Development, 1965, 30, (100), 82-101.

Zargar, A.M. Planning in human performance. Grammatical expectancies during reading. Unpublished doctoral dissertation, Department of Industrial Engineering, Stanford University, 1973.

Zelniker, T., Jeffrey, W.E., Ault, R., and Parsons, J. Analysis and modification of search strategies of impulsive and reflective children on the Matching Familiar Figures Test, Child Development, 1972, 43 (2), 321-335.

Zinchenko, V.P., Chzhi-Tsin, V., and Tarakanov, V.V. The formation and development of perceptual activity. Soviet Psychology and Psychiatry, 1963, 2, 3-12.

Zusne, L., and Michels, K.M. Nonrepresentational shapes and eye movements. Perceptual and Motor Skills, 1964, 18, 11-20.

APPENDIX

SURVEY OF EYE MOVEMENT RECORDING METHODS

Laurence R. Young
Department of Aeronautics and
Astronautics
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

and

David Sheena
Whittaker Corporation
Space Sciences Division
335 Bear Hill Road
Waltham, Massachusetts 02154

April 1975

Prepared for

Conferences on Eye Movement Research and Technology
Task Force on Essential Skills
National Institute of Education

This material is expected to appear in the September 1975 issue of Behavior Research Methods and Instrumentation. It is reproduced here with the permission of Psychonomic Society Journals.

TABLE OF CONTENTS

Section			Page
		List of Illustrations	iv
1		INTRODUCTION	1-1
2		TYPES OF EYE MOVEMENT (From Young, 1970)	2-1
3		PHYSICAL CHARACTERISTICS OF THE EYE WHICH ARE USED IN EYE MOVEMENT MEASUREMENT	3-1
	3.1	The Retina	3-1
	3.2	Corneo-Retinal Potential	3-1
	3.3	Electrical Impedance	3-2
	3.4	The Corneal Bulge	3-2
	3.5	Corneal Reflections	3-3
	3.6	Reflections from Other Optical Curvatures in the Eye - Purkinje Images	3-3
	3.7	The Limbus	3-4
	3.8	The Pupil	3-4
	3.9	Other Optical and Non-Optical Landmarks	3-5
4		MAJOR EYE MOVEMENT MEASUREMENT TECHNIQUES	4-1
	4.1	Electro-Oculography	4-1
		4.1.1 Principle	4-1
		4.1.2 Implementation	4-1
		4.1.3 Evaluation of Electro-Oculography	4-3
	4.2	Corneal Reflection	4-6
		4.2.1 Principle	4-6
		4.2.2 Specific Implementations	4-8
		4.2.2.1 Laboratory Corneal Reflex Camera	4-9
		4.2.2.2 Head Mounted Corneal Reflex Camera	4-11
		4.2.3 Evaluation of Corneal Reflex Methods	4-14
	4.3	Limbus, Pupil and Eyelid Tracking	4-18
		4.3.1 Basic Techniques	4-18
		4.3.2 Specific Implementations	4-19
		4.3.2.1 Scanning Methods	4-19
		4.3.2.2 Differential Reflection Methods	4-24
		4.3.3 Evaluation of Limbus and Pupil Tracking Techniques	4-29
	4.4	Contact Lens Method	4-32
		4.4.1 Basic Techniques	4-32
		4.4.2 Specific Implementations	4-33
		4.4.3 Evaluation of Contact Lens Method	4-38
	4.5	Point of Regard Measurement: Tracking of Corneal Reflection Center with Respect to the Pupil Center	4-38
		4.5.1 General Principle	4-38
		4.5.2 Specific Implementations	4-39
		4.5.3 Evaluation of the Corneal Reflection-Pupil Center Measurement	4-51

TABLE OF CONTENTS (Cont'd)

Section			Page
	4.6	Measurement of Eye Rotation by the Double Purkinje Image Method	4-53
		4.6.1 Principle	4-53
		4.6.2 Implementation	4-55
		4.6.3 Evaluation of the Double Purkinje Image Eye Tracker	4-55
	4.7	Measurement of Fixation Point by Determining the Rotation of a Plane Attached to the Eye	4-58
		4.7.1 General Principles	4-58
		4.7.2 Specific Implementations	4-58
		4.7.2.1 Ellipticity of the Pupil	4-58
		4.7.2.2 Contact Lens Method	4-60
		4.7.2.3 Tracking of a Retinal Image	4-60
	4.8	Head Movement Measurement to Obtain Point of Regard	4-63
		4.8.1 Optical Head Position Sensors	4-64
		4.8.2 Ultrasonic Head Position Sensors	4-67
		4.8.3 Mechanical Head Position Sensors	4-69
		4.8.4 Inertial Head Position Sensors	4-72
		4.8.5 Electromagnetic Head Position Sensors	4-72
5		TRADE OFFS AND GENERAL CONSIDERATIONS IN INSTRUMENTATION SELECTION FOR READING RESEARCH	5-1
	5.1	Tradeoffs	5-1
	5.2	Simultaneous Psycho-physiological Measurement	5-3
6		COMPARATIVE TABLES OF EYE MOVEMENT MEASUREMENT TECHNIQUES	6-1
Appendix A		SCHEMATIC OF THE EYEBALL	A-1
		REFERENCES AND TITLES OF FIGURES	R-1

LIST OF ILLUSTRATIONS

Figure		Page
2.1	Typical Horizontal Eye Movements Recorded with a Photoelectric Monitor, Showing Saccadic Jumps, Fixation Movements, Smooth Pursuit, and Optokinetic Nystagmus	2-4
4.1	A Method for Reducing Cross Coupling in Conjugate Electro-oculography	4-5
4.2	Corneal Reflection Geometry	4-7
4.3	The AO Ophthalmograph	4-10
4.4	Continuous Moving Film Record of Corneal Reflections	4-10
4.5	Eye Marker Camera	4-12
4.6	Mobile Corneal Reflex Eye Movement Camera	4-13
4.7	Head Mounted Corneal Reflex Illumination, Viewing and Combining Optics	4-15
4.8	Head Mounted Corneal Reflex System with Miniature TV Camera	4-16
4.9	Schematic Diagram for Head Mounted TV Corneal Reflex System	4-16
4.10	TV Picture of a Bright Pupil	4-20
4.11	Scanning Method for Tracking Limbus	4-21
4.12	Various Scan Methods Applied to Tracking the Limbus and Pupil	4-23
4.13	Differential Reflection Reading Eye Movement Measurement Device	4-25
4.14	Light and Photocell Arrangement for Limbus Tracking	4-27
4.15	Spectacle Mounted Differential Reflectivity Device	4-27
4.16	Limbus Tracking with Bifurcated Fiber Optics	4-28
4.17	Tracking of the Lower Lid	4-28
4.18	Tracking of the Limbus Image	4-30
4.19	Position of Detector Fiber Bundles on Eye Image	4-30
4.20	Illumination Pattern for Two-dimensional Limbus Tracking	4-31

LIST OF ILLUSTRATIONS (Cont'd)

Figure		Page
4.21	Plane Mirror Attached to Scleral Lens	4-35
4.22	Line Diagram Fixed to the Eyeball by Means of the Scleral Contact Lens	4-37
4.23	The Modified Photonystagmographic Method of Forgacs	4-37
4.24	Photograph from Wide Angle Mackworth Camera	4-41
4.25	Illustration of a System for Recording Eye Behavior in Infants	4-41
4.26	An Illustration of a Procedure for Recording Eye-To-Eye Contact Between Mother and Child	4-43
4.27	Displacement of Corneal Reflection from Center of Pupil	4-44
4.28	Effects of Eye Translation and Rotation on Corneal Reflection-Pupil Center	4-45
4.29	Operator Indicators Superimposed on TV Image of Eye as a Function of Threshold Setting Showing Status of Measurement	4-47
4.30	Schematic of the Cubic Foot Remote Oculometer	4-49
4.31	EG&G-HEL Oculometer System	4-50
4.32	Simple Field Representation of Cornea and Rear Surface of Lens	4-54
4.33	Schematic Layout of the Double Purkinje Image Eye Tracker	4-56
4.34	Apparent Ellipticity of Pupil as Eye Rotates	4-59
4.35	Scanning of a Retinal Vessel	4-61
4.36	Fundus Tracking System	4-61
4.37	Circular Scan X-Y Tracker	4-65
4.38	Optical Head Position Sensor	4-66
4.39	Head Line-of-Sight Sensing System	4-68
4.40	LED Line of Sight Head Position Measurement System	4-70
4.41	Ultrasonic Head Position Measurement System	4-70
4.42	"Pipestem" Bite Board Device for Head Position Measurement Incorporated with an Eye Movement Device	4-71
A-1	Schematic and Optical Constants of the Eyeball	A-1

1 INTRODUCTION

The importance of eye movement patterns in the study of reading and in the diagnosis of reading disabilities is widely recognized. This paper reviews most of the known techniques for measuring eye movements, explaining their principle of operation and their primary advantages and disadvantages.

Section II describes the various types of eye movement. Section III reviews the characteristics of the eye which lend themselves to measurement and lists all the principal eye movement measurement approaches. Section IV describes the more practical methods in some detail with considerable attention on the newer techniques. Section V discusses the general considerations of method selection. Section VI summarizes the major findings in a concise table.

2 TYPES OF EYE MOVEMENT (from Young, 1970)

For any application of eye-movement instrumentation the kinds of eye movements to be observed must be clearly understood so that the instrument specifications may be properly assigned. The following list summarizes the types of known eye movements. Eye movements are considered here as rotations about a horizontal axis, an (initially vertical) axis which rotates with the globe about the horizontal, and a torsion axis along the angle of gaze. The eye does not rotate about a fixed center, but this is not of practical importance for most measurement applications (Park and Park, 1933). Several types of horizontal eye movements are illustrated in Figure 2.1.

Saccadic eye movements are the rapid conjugate movements by which we change fixation from one point to another voluntarily. They include the "jump and rest" fixation movements observed in scanning a visual scene or reading. They are characterized by very high initial acceleration and final deceleration (up to $40{,}000^{o}/sec^{2}$) and a peak velocity during the motion which varies with the amplitude of the saccade and may be as high as 400 to 600^{o}/sec. The duration of a saccadic eye movement also varies with its magnitude from 30 to 120 msec (Mackensen, 1958). Saccadic eye movements generally observed in searching are of the range 1 to 40^{o}. Head motion is often involved when the target motion exceeds 30^{o}. In response to a visual stimulus, saccadic eye movements exhibit a latency of 100 to 300 msec. Vertical or oblique saccadic eye movements may have a torsional component associated with them because of the arrangement of the six extraocular muscles. The purpose of the saccadic eye-movement system appears to be fixation of the image of the target on the fovea, or high-acuity region of the retina, corresponding to 0.6 to 1^{o} of visual angle. There is a minimum delay or refractory period between saccadic eye movements of 100 to 200 msec. The visual threshold is significantly elevated during the period just prior to and during a saccadic eye movement (Young, Zuber and Stark, 1966; Cook, 1965; Robinson, 1964;Vossius, 1960.).

Pursuit, or slow tacking, movements are conjugate eye movements used to track slowly moving visual targets in the range 1 to 30°/sec. Pursuit movements are smoothly graded and appear to partially stabilize the image of the moving target or background on the retina, independent of the saccadic eye-movement system. The pursuit-movement system appears to be limited in acceleration as well as velocity. Smooth pursuit movements are not generally under voluntary control and usually require the existence of a moving visual field for their execution (Westheimer, 1954; Robinson, 1965).

Compensatory eye movements are smooth movements closely related to pursuit movements, which compensate for active or passive motion of the head or trunk. They tend to stabilize the retinal image of fixed objects during head motion and are attributable both to semicircular-canal stimulation sensing head motion and to neck proprioception associated with the turning of the head on the trunk. Compensatory eye movements are also limited to about 30°/sec and are closely related to the slow-phase eye movements of vestibular nystagmus discussed below.

Vergence eye movements are movements of the two eyes in opposite directions in order to fuse the image of near or far objects. The vergence movements are considerably slower and smoother than conjugate eye movements, appear to be non-predictive, and reach maximum velocities on the order of 10°/sec over a range of nearly 15°. They are stimulated by focusing error (accommodative convergence) as well as binocular disparity (Rashbass and Westheimer, 1961; Zuber and Stark, 1968).

Miniature eye movements, or fixation movements, include a variety of motions which are generally less than 1° in amplitude and occur during attempted steady fixation on a target. Drift is the slow random motion of the eye away from a fixation point at velocities of only a few minutes of arc per second occurring within the foveal dead zone. Flicks, or microsaccades, are small, rapid eye movements which have been shown to be dynamically of the same nature as large voluntary saccades, of magnitudes as large as 1°, occurring at intervals separated by as

little as 30 msec and which generally redirect the eye toward the position necessary for fixation on the target (Zuber, 1965). Both flicks and drifts tend to occur along a single preferred axis in any individual (Nachmias, 1959). There is currently no general agreement on the error-correcting nature of the flicks or drifts. In addition, normal individuals fixating on targets exhibit a high-frequency tremor in the range of 30 to 150 Hz with peak amplitudes of approximately 30 arc sec in the region of 70 Hz. (Because of the presence of these fixation movements, accuracy of 0.5 to 1° is often sufficient in eye-monitoring tasks designed to show what part of the visual field is being fixated.)

Optokinetic nystagmus, also known as "train nystagmus", is a characteristic sawtooth pattern of eye motion elicited by a moving visual field containing repeated patterns. Optokinetic nystagmus consists of a slow phase, in which the eye fixates on a portion of the moving field and follows it with pursuit motion, and a fast phase or return saccadic jump in which the eye fixates on a new portion of the field. The minimum time between fast phases is approximately 0.2 sec, resulting in a maximum frequency of approximately 5 Hz. although the nystagmus frequency may be considerably less for slow field motions. The amplitude of optokinetic nystagmus is variable, generally from 1 to 10°. If a non-moving fixation point is present in the visual field, the nystagmus response may be reduced to a fraction of a degree, which is not noticeable by direct observation. Attempts have been made to use optokinetic nystagmus as an objective measurement of visual acuity by determining the minimum line width which induces nystagmus.

Figure 2.1 shows typical single-eyed horizontal eye movements recorded by the photoelectric technique. The rapid saccadic jumps and fixation movements are seen in the early part of the trace, followed by smooth pursuit movements in tracking a target, and finally optokinetic nystagmus induced by horizontal movement of a sheet of lined paper.

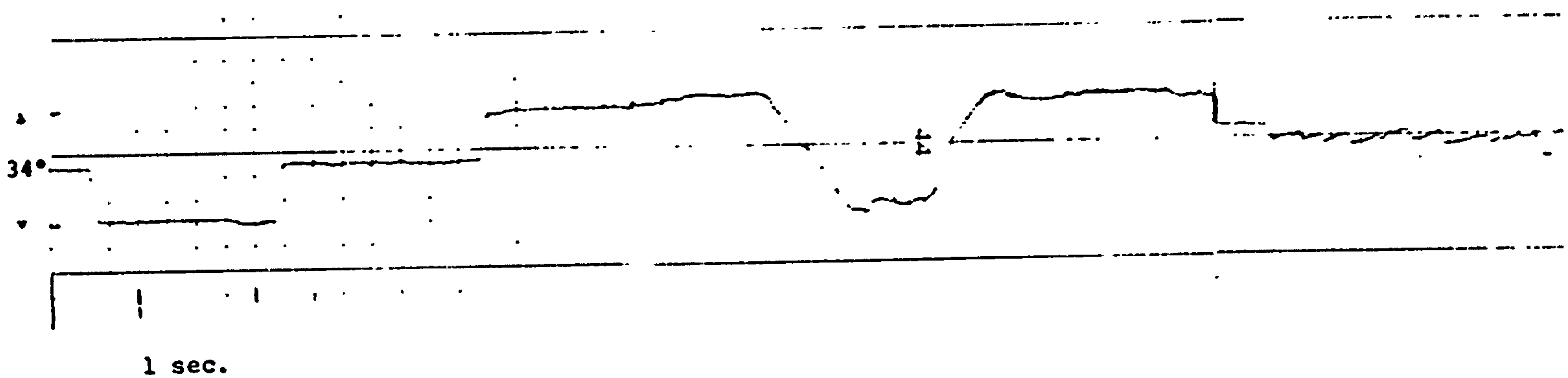


Figure 2.1. Typical horizontal eye movements recorded with a photoelectric monitor, showing saccadic jumps, fixation movements, smooth pursuit, and optokinetic nystagmus. From "Recording Eye Position," Biomedical Engineering Systems, Clynes & Milsum ed. Copyright 1970, McGraw Hill Book Company. Used with permission of McGraw Hill Book Company.

Vestibular nystagmus is an oscillatory motion of the eye, similar in appearance to optokinetic nystagmus, containing a slow phase and a fast saccadic-like return. It is primarily attributable to stimulation of the semicircular canals during rotation of the head with respect to inertial space. A counter-clockwise head rotation about a vertical axis leads to deflection of the cupulas of the horizontal semicircular canals, which induces image-stabilizing slow-phase eye movement in a clockwise direction. As head motion continues, the eyes jump back rapidly to pick up another position and repeat the sawtooth pattern. Measurement of vestibular nystagmus in various axes is a commonly used test of the semicircular-canal function, either through the threshold of angular acceleration impulse required to induce nystagmus or through the duration of "postrotation nystagmus". The latter test constitutes a part of the nystagmus or objective cupulogram. The amplitude and frequency of vestibular nystagmus are similar to those of optokinetic nystagmus. It has recently been demonstrated that vestibular nystagmus can be induced by pure linear acceleration and by a rotating linear-acceleration vector; the former may reflect otolith contribution, while the latter is attributable to deformation of the semicircular canals (Young, 1969; Steer, 1967). A variety of rotational tests are used with eye-movement measurements to indicate the pathology of the nonauditory labyrinth. A related type of eye movement induced in the clinical situation is caloric nystagmus. The external semicircular canals are stimulated by the convection currents induced in the canals upon introduction of water above or below body temperature into the external ear. The temperature change necessary to induce nystagmus and the duration and strength of nystagmus for standard temperatures consitute a set of clinical measurements useful in the diagnosis of vestibular disease.

Spontaneous nystagmus, or gaze nystagmus, is an anomaly of nystagmus associated with a number of neurological disorders. This nystagmus may be either

large enough for direct observation or less than 1^{o}, requiring recording for detection. Gaze nystagmus is observed only when the subject looks in a certain direction. The nystagmus may be either asymmetric, containing a slow phase and a fast phase, or "pendular," showing fine high-frequency oscillations of 4 to 10 Hz. Some of these abnormal eye movements are too small to be observed in close clinical examination and are important diagnostically. Recording of nystagmus as well as the ability of subjects to follow targets with normal saccadic and pursuit tracking promises to become more widespread.

Torsional eye movements are rotation movements of the eye about the line of gaze, and they are generally limited to angles of less than 10^{o}. The rolling motions may be stimulated by rotational optokinetic nystagmus or by two types of vestibular responses. The torsional component of vestibular nystagmus or compensatory eye movement in response to head rotation is similar to the horizontal and vertical vestibular nystagmus mentioned above. In addition, the phenomenon of counterrolling or steady-state offset of the eye about the torsional axis in response to tilt of the head with respect to the vertical, has been demonstrated and shown to be attributable to the human otolith or vestibular gravity receptors. As such it has been suggested as an important measurement of otolith function (Woellner and Graybiel, 1959).

3 PHYSICAL CHARACTERISTICS OF THE EYE WHICH ARE USED IN EYE MOVEMENT MEASUREMENT

3.1 The Retina

The eye has no proprioceptive feedback, in terms of conscious position sense. It does, however, contain the retina which moves with the eye and makes possible the subjective assessment of eye movement. Among the earliest quantitative techniques for determining the velocity of the eye during pursuit and saccadic eye movements was the use of after-images. A small light, flashed periodically, will leave a trace of after-images, the density of which indicates fixation duration and the spacing of which indicates the velocity of eye movements. After-images separated by as little as 15 arc minutes can be resolved, and the technique is usable over the entire range of eye movements. It's chief drawbacks are, of course, the subjective nature of the measurement and the fact that it can only be used for a brief interval, after which the subject must report on the number and placement of his after-images. It is of practical use currently only for the measurement of ocular torsion where it provides a convenient and relatively accurate measurement and for which there are no readily available automatic methods which are economical, simple to apply, and easily analyzed.

The fovea contains thousands of light absorbing radially oriented crystals which selectively absorb linearly polarized light. Kaufman and Richards (Richards and Kaufman, 1969; Kaufman and Richards, 1969) used rotating polarized blue light to form a "spinning propeller" after image relative to the subject's fovea to determine fixation points.

3.2 Corneo-Retinal Potential

A potential difference of up to 1 mv between the cornea and the retina (cornea positive) normally exists in the eye, and is used as the basis of the most widely applied clinical eye movement technique - electro-oculography. The precise basis of this potential difference,once attributable to the electrical activity of the retina itself, is now in question once again. This potential has important variations diurnally and also with the level of light adaptation, decreasing following steady periods in the dark (Gonshoor and Malcolm, 1971).

For stable electro-oculographic measurements, especially in the dark, the subject should be permitted to adapt to the ambient illumination level to be used in the experiment for thirty to sixty minutes prior to the experiment.

The negative electrical pole lies approximately at the optic disk, 15 degrees displaced from the macula. Since the electric field is not aligned with the optic axis any torsional rotation of the eye introduces a potential change which can be mistaken for horizontal or vertical eye movement. This very geometry, however, makes electro-oculography a possible, though difficult method for measuring ocular torsion (Gabarsek, 1970).

3.3 Electrical Impedance

The impedance measured between electrodes placed at the outer canthi of the two eyes varies with eye position. The variation in this resistive component is either associated with the non-homogeneous or anisotropic nature of electrical characteristics of the tissues in the globe or with the non-spherical characteristics of the globe so that the resistivity of the path between the two electrodes changes with position (Sullivan and Weltman, 1963; Geddes et al, 1965).

3.4 The Corneal Bulge

The cornea, attached to the sclera at the front of the eye and centered close to the optic axis, has a smaller radius of curvature than the eye itself. This forms the basis for a number of important methods of eye movement measurement. In the early days of research on eye movements, attachments were made directly to the cornea by a plaster of paris ring and mechanical linkages to recording pens (Delabarre, 1898). The bulge of the cornea can be felt through the eyelid of the closed eye, and pressure transducers placed over the eyelid can detect these changes. In more recent times, the cornea has acted as a mechanical post to center tight fitting scleral contact lenses to which other measurement devices are attached. It should

be noted that the cornea itself slips slightly with respect to the sclera when forces are applied to the cornea, and probably slips slightly during the eye acceleration phase of saccadic eye movements. Contact lenses applied to the cornea itself are not an adequate base for the accurate measurement of eye position, and large contact lenses conforming to the sclera as well as the cornea are necessary for systems in which stability of better than a few minutes of arc is desired. The nominal curvature of the cornea for an adult human is approximately 8 mm radius for an eye of 13.3 mm radius. Once a contact lens is fitted, its position can be measured by any of a number of methods.

3.5 Corneal Reflections

The front surface of the cornea, although not a perfect optical surface, approximates a spherical section over its central 25 degrees. As with a convex mirror, reflections of a bright object from this surface form a virtual image behind the surface which can be imaged and photographed or recorded. The position of the image commonly seen as the highlight in the eye, the corneal reflection, is a function of eye position. Rotation of the eye about its center produces a relative translation as well as rotation of the cornea, forming the bases for the important class of eye movement instruments known as corneal reflection systems.

3.6 Reflections from Other Optical Curvatures in the Eye - Purkinje Images

Although the brightest reflections of incident light come from the front surface of the cornea, light is also reflected from each surface of the eye at which there is a change in refractive index. Reflections come also from the back surface of the cornea, the front surface of the lens and the rear surface of the lens. These four are referred to as the Purkinje Images.

After the bright front surface reflection, the next most visible Purkinje image is the fourth, coming from the posterior surface of the lens. Measurements of the relative displacement between the first and fourth images, representing as they do, points focused imaged from planes of different depths in the eye, represent one technique for actively measuring the orientation of the eye in space independent of its relation to head position.

3.7 The Limbus

The iris of the eye is normally visible and clearly distinguishable from the sclera, and is the basis for the normal visual assessment of the angle of gaze. The position of the iris-scleral boundary (the limbus) may be measured with respect to the head. The ratio between dark iris and bright sclera observed on the left and right side of the eye may either be measured directly with photosensors or indirectly on an image of the eye. This ratio is directly related to the horizontal position of the eye. The best wavelength for making the distinction between iris and sclera depends to some extent on the iris color, however, mixed white light is normally reasonably effective.

3.8 The Pupil

The pupil is easily distinguished from the surrounding iris by its difference in reflectance. The pupil can be made to appear much darker than the iris under most lighting conditions when the majority of light does not come in directly along the axis of measurement, and consequently is not reflected out. On the other hand, the pupil can be made to appear very bright (as often seen in amateur full-face flash photography) when most of the light enters along the optic axis and is reflected back from the retina. In either case the pupil can be separated from the surrounding iris optically. This can be especially sharpened with the use of infra-red light which will be nearly entirely absorbed once entering the eye, consequently make the pupil much darker than the surrounding iris. The pupil normally varies between 2 and 8 mm in diameter in adult humans. Although it is actually slightly elliptical in shape, it can be

approximated closely by tracing the best fitting circle to the pupil circumference with an image dissector technique. The center of the pupil is also easily located electro-optically or on film for hand analysis.

The pupil appears elliptical when viewed other than along the optic axis, with the minor axis shortening in the axis of eye rotation. The pupil eccentricity could serve as a basis for eye angle measurement.

3.9 Other Optical and Non-Optical Landmarks

In addition to the iris and the pupil, other optical landmarks can be traced. Scleral blood vessels or folds of the iris can be identified by hand or traced with optical tracing techniques. (These are of practical application only in the measurement of ocular counterrolling.) The retinal vessels which can also be imaged and tracked, provide one of the most accurate techniques for determining the place on the retina where a given target is imaged and consequently the exact fixation point of the eye. The retinal vessels, approximately 0.2 mm in diameter, radiate from the optic disk.

Some artificial landmarks have also been placed on the eye, and their positions recorded. A globule of mercury (Barlow, 1952), chalk and egg membrane have been used for optical tracking. A small piece of metal imbedded in the sclera has been used for magnetic tracking of eye position.

4. MAJOR EYE MOVEMENT MEASUREMENT TECHNIQUES

4.1 Electro-Oculography

4.1.1 Principle

Schott (1922) and Mowrer, Ruch, and Miller (1936) found that the position of the eye could be measured by placing skin electrodes around the eye and recording potential differences. The source of the electrical energy is the corneoretinal potential, or electrostatic field which rotates with respect to the eye. The cornea remains 0.40 to 1.0 mv positive with respect to the retina; this is attributable to the higher metabolic rate at the retina. As the eye rotates, the electrostatic dipole rotates with it, and consequently the potential difference in a plane normal to the principal axis varies, theoretically, as the sine of the angle of deviation. Of course, the nonhomogeneous nature of the conducting medium causes wide departure from the theoretical values. These techniques were reviewed by Marg (1951) and more recently by Kris (1960). Skin electrodes placed on the outer canthi measure conjugate horizontal eye position. By reference to any third electrode over the bridge of the nose, some measure of horizontal eye vergence may also be detected. The recorded potentials are small, in the range of 15 to 200μv with nominal sensitivities of the order of 4 μv per degree of eye movement.

4.1.2 Implementation

The signals are at times difficult to detect in the presence of large muscle-action-potential artifacts, also picked up as potential differences by the skin electrodes (Shackel, 1960). The presence of external electrical interference is troublesome unless care is taken to shield the system.

Normally, but not always, the DC recording method, which is necessary to determine eye position is referred to as electro-oculography (EOG), AC recording, which is useful for measurement of eye movement, including the fast and slow phases of nystagmus, is referred to as electronystagmography (ENG).

Up until recent years, the problem of drift in both electrodes and DC amplifiers made DC recording a difficult and frustrating practice. Gross patterns of reading movements (number of saccades per line, number of regressions and fixation durations) can easily be obtained from AC recording with time constants of 3 - 10 seconds or more. With longer time constants, even the approximate position on a line can be determined. An advantage of AC recording is that a high sensitivity recording can be made without fear of having the record drift off scale.

DC recording has recently been made much more practical with two electronic advances. New skin electrodes, especially silver-silver chloride (Beckman or Becton-Dickinson for example) are easily applied with adhesive tape rings, require no skin preparation other than cleaning with alcohol or acetone, are of minimual discomfort, and resist excessive polarization over many minutes of use. They also seem to be relatively less sensitive to changes in skin resistance when led into any of the newer high input impedance (FET) preamplifiers. Gold plated electrodes are also in use (Toglia, 1973). Placement of a high common mode rejection preamplifier very close to the subject's head, proper grounding of the subject through an ear electrode, and use of shielded cable can help eliminate the disturbance from electromagnetic pick-up.

Conjugate horizontal eye movements are recorded between electrodes at the outer canthi of the eyes. Placement of the electrodes further back toward the temples reportedly reduces the artifacts from muscle activity. Separate recording of the horizontal movements of each eye is generally performed with the use of a third common electrode placed over the bridge of the nose.

When both vertical and horizontal recording from one or both eyes is performed, the errors introduced by coupling between the axes and by the nonlinearity of the records can be considerable. Some improvement in the

cross coupling results from the use of "vector electrooculography" introduced by Uenoyama, Uenoyama, and Iinuma (1964) and extended by Jeannerod et al (1966). In addition to simultaneously displaying the x and y coordinates of eye movements, they electrically short circuit the two superior electrodes and the two inferior electrodes for the vertical eye-movement recording as seen in Figure 4.1. A commonly observed overshoot artifact in EOG recording of vertical eye movements has been attributed to the motion of the upper eyelid.

An alternative combination of electrode outputs has been found useful for simultaneous separate recording of the vertical and horizontal movements of each eye (Bles and Kapteyn, 1973). By combining the individual electrode outputs of Figure 4.1, as indicated below, one can choose β and γ during calibration to virtually eliminate the effect of vertical eye movements:

Right eye vertical: $D - E$

Left eye vertical: $F - G$

Right eye horizontal: $(A - C) + \beta(D + E)$

Left eye horizontal: $(C - B) + \gamma(F + G)$

For animal work, the stability and signal to noise ratio of electro-oculography can be improved considerably by the use of fine platinum needle electrodes in the skin around the orbit or by the use of miniature permanently implanted silver-silver chloride electrodes placed in holes in the bony orbit (Bond and Ho, 1970).

4.1.3 Evaluation of Electro-Oculography

EOG has the largest range of any of these objective methods practical for human studies, since it does not require visualization of the eye. The method is usable for eye movements up to ±70 degrees (Wolf and Knemeyer, 1969). Linearity becomes progressively worse at excursions greater

than 30 degrees, especially in the vertical. Typical accuracy with surface electrodes is ± 1.5 - 2 degrees.

The chief sources of error are muscle artifacts, eye lid interferences, basic nonlinearity in the technique and variation in the corneoretinal potential attributable to light adaptation, diurnal variations and the state of alertness.

Potential improvement in EOG performance could come with the making of integrated electrode amplifier assemblies attached directly to the skin to eliminate noise susceptibility and minimize shielding requirements.

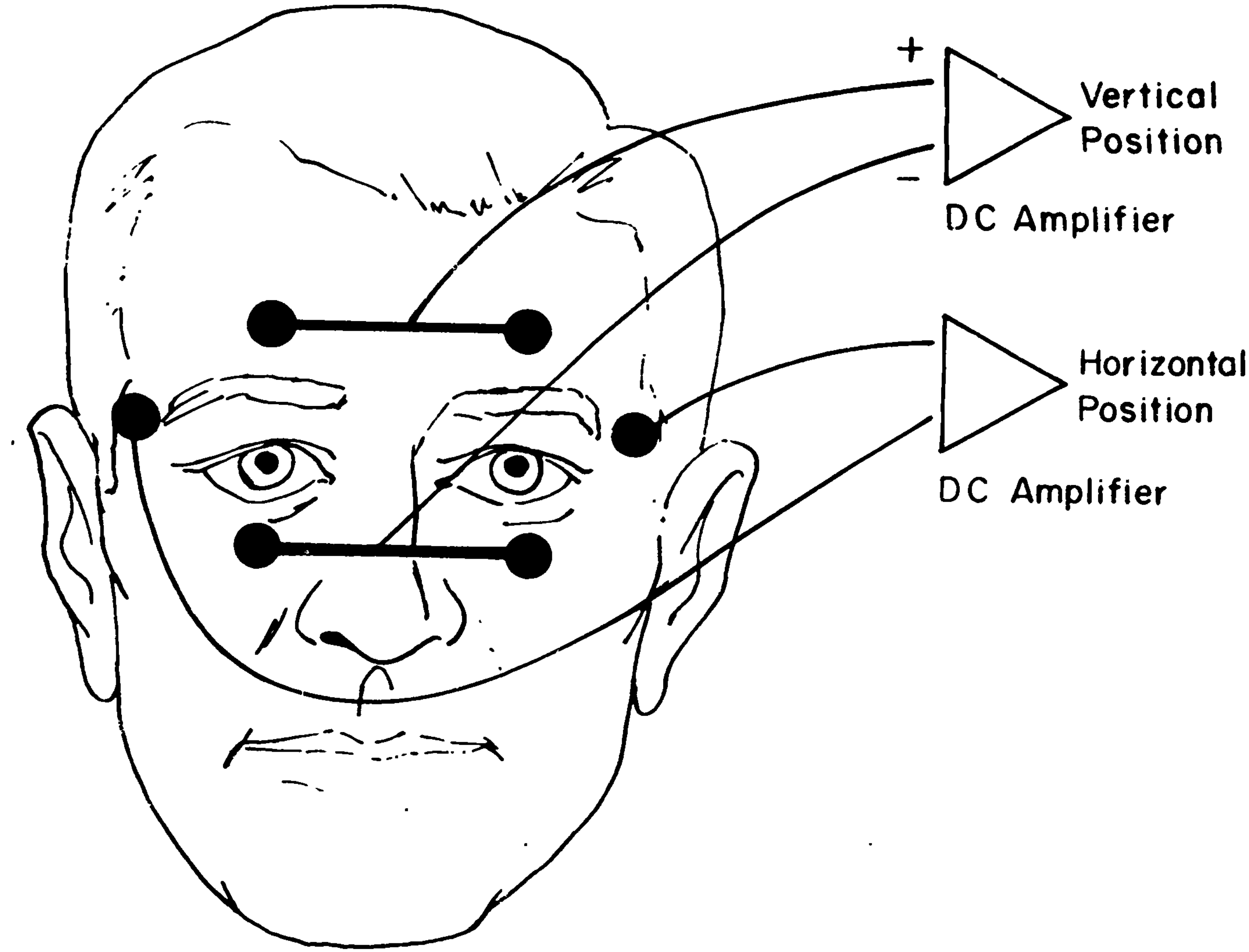


Figure 4.1. A Method for Reducing Cross Coupling in Conjugate Electro-Oculography. (Young 1970 after Jeannerod et al. 1966)

4.2 CORNEAL REFLECTION

4.2.1 Principle

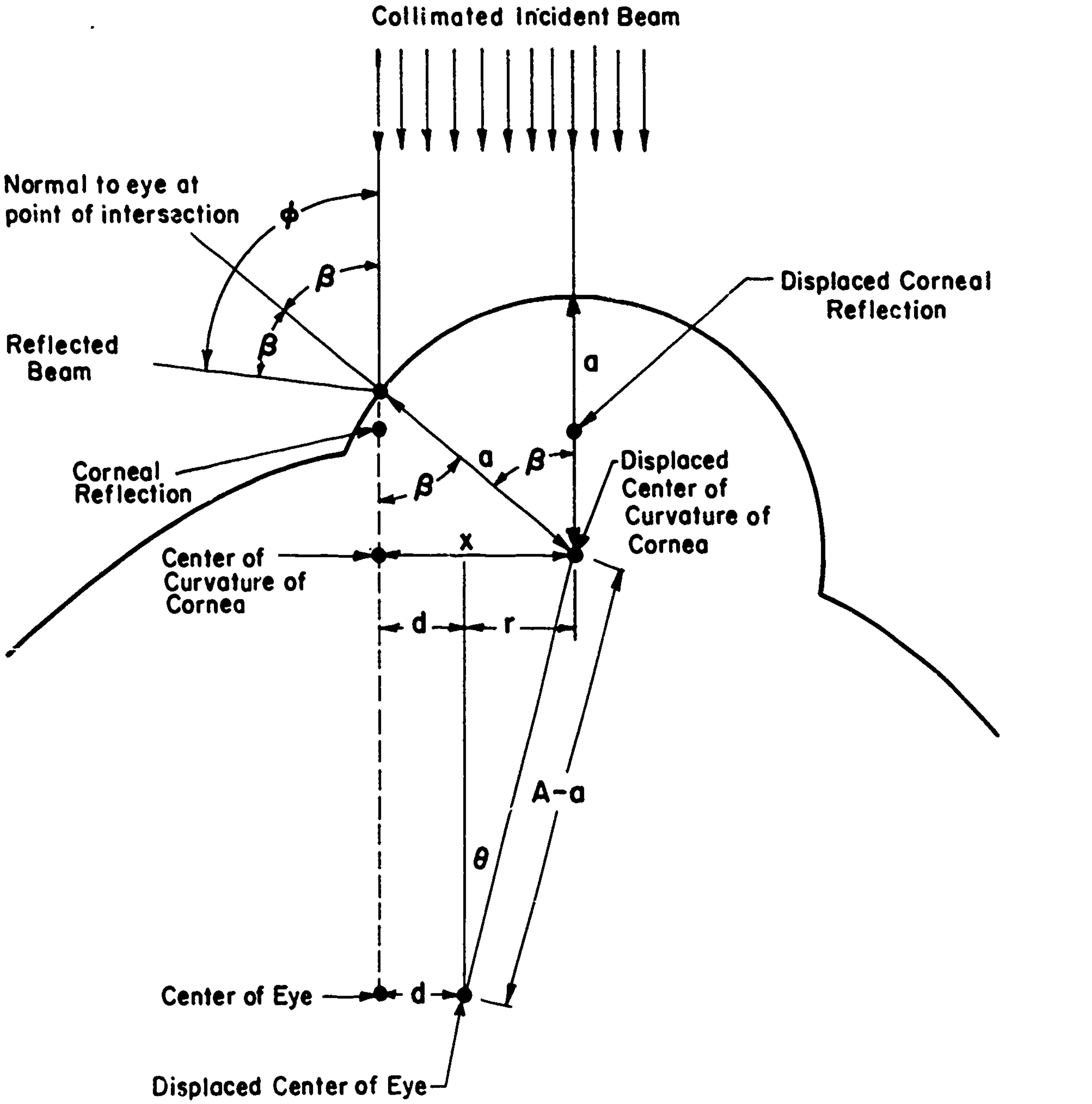
The corneal bulge produces a virtual image of bright lights in the visual field and region. Because the radius of curvature of the cornea is less than that of the eye, the corneal reflex moves in the direction of eye movement, relative to the head. Since it only moves about half as far as the eye, it is displaced opposite to the eye movement relative to the optic axis or the center of the pupil as seen in the accompanying figures.

The geometry of the corneal reflex principle is seen by reference to the accompanying Fig.4.2. Incident light from a source L (which is here shown to be collimated for illustration) is reflected from the convex surface of the cornea in a pattern of diverging light and is imaged through a concave lens onto a film plate, television camera element or photocells (Carmichael and Dearborn, 1947; American Optical, 1937; Taylor, 1971). An incident ray is reflected at an angle ϕ which varies with the displacement (x) of the center of curvature of the cornea perpendicular to the incident ray. As seen in the diagram, this displacement consists of two parts, a displacement (r) resulting from eyeball rotation relative to the light source, and a displacement (d) equal to the linear displacement of the center of rotation of the eye normal to the incident ray. The apparent displacement of the corneal reflection to a stationary observer is $x = d + (A-a)\sin\theta$. The expected relationship among reflection angle (ϕ) of a single beam of light, eye rotation (θ) and lateral diaplacement of the center of the eye (d) is

$$\sin\phi = 2\left\{\left(\frac{A}{a} - 1\right)\sin\theta + \frac{d}{a}\right\}$$

Usually the small angle approximation for ϕ as well as θ is used (Ditchburn and Ginsborg, 1953) yielding

$$\phi \approx 2\left\{\left(\frac{A}{a} - 1\right)\theta + \frac{d}{a}\right\}$$



$$x = d + r$$

but $r = (A-a)\sin\theta$

$$\boxed{x = d + (A-a)\sin\theta}$$

$$\sin\beta = x/a$$

$$\phi = 2\beta$$

$$\phi = 2\sin^{-1} x/a$$

$$\phi = 2\sin^{-1}\left(\left(\frac{A}{a}-1\right)\sin\theta + \frac{d}{a}\right)$$

$$\sin\frac{\phi}{2} = \left(\left(\frac{A}{a}-1\right)\sin\theta + \frac{d}{a}\right)$$

for small angles, $\sin\theta \approx \theta$

$$\sin\frac{\phi}{2} = \left(\left(\frac{A}{a}-1\right)\theta + \frac{d}{a}\right)$$

or

$$\boxed{\phi = 2\left(\left(\frac{A}{a}-1\right)\theta + \frac{d}{a}\right)}$$

d = lateral displacement of eye center

r = lateral displacement of center of curvature of cornea due to rotation

A = radius of the eye (from center of rotation to outer central surface of cornea ($\sim$13.3 mm)

a = radius of curvature of outer surface of cornea ($\sim$ 8 mm)

Figure 4.2. Corneal Reflection Geometry

which is valid only for small eye rotations and for small ϕ, meaning that the reflected beam is close to the incident beam. For side lighting, with a large initial angle of reflection (ϕ_0), the appropriate equation is

$$\sin(\phi_0 + \Delta\phi) = 2\{(\frac{A}{a} - 1)\sin\theta + \frac{d}{a}\}$$

or

$$\Delta\phi \simeq 2\{(\frac{A}{a} - 1) + \frac{d}{a}\}/\cos\phi_0$$

for small eye rotations θ and any initial reflection angle.

The lateral head movement factor ($\frac{d}{a}$) can contribute a large error when the head moves relative to the light. Ditchburn and Ginsborg point out that, with A = 13.3 mm and a = 8.0 mm

$$\phi = 1.3\theta + 860d$$

with ϕ and θ measured in arc minutes and d in mm. (1 mm change in head position is equivalent to an eye rotation of greater than 12 degrees.) For this reason many of the fixed head versions and the head mounted devices require accurate stabilization of the light source and recording device with a bite board or head strap.

4.2.2 Specific Implementations

There are two basic types of corneal reflex methods, depending on the location of the light source. In the first, and oldest, the light source is fixed with respect to the subject's head. To relate eye position to the material being fixated therefore requires either a fixed head system, a method for recording head position (linear and angular) or a technique for recording the field of view relative to the head at every sample. These methods are referred to as head mounted or head fixed corneal reflex techniques.

The second corneal reflex method fixes the light source in the target field rather than to the head. By placing the light source in the target field, movements of the corneal reflex relative to the pupil indicate the point of regard of the eye in the field, and not relative to the head. These techniques

are referred to as corneal reflex point of regard instruments, and are much less sensitive to head position. They are described in detail in Section 4.5.

4.2.2.1 <u>Laboratory Corneal Reflex Camera</u>

In the early AO Ophthalmograph, and its descendent, the Reading Eye I, the head was fixed with a chin rest and head rest, and reading material was presented on fixed index cards. Small dim lights located temporally in the peripheral field reflected corneal highlights which were imaged by a camera. (See Figure 4.3). The horizontal motion of the corneal reflex of each eye is recorded as a time trace on moving film, yielding a record such as that shown in Figure 4.4 . Vertical and horizontal scan patterns can be shown simply by stopping the film for a period. Timing marks can be added by periodic interruptions of the light.

As a variation of the basic corneal reflection technique to permit continuous monitoring of vertical as well as horizontal eye motion, the corneal reflex is split into two beams by prisms. One beam is recorded on vertically moving film to yield horizontal eye movements, and the second beam is directed to a horizontally moving film to record vertical movements (Buswell, 1935).

One laboratory Mackworth Camera is presently available, the Polymetric Eye Movement Recorder V-1164. It provides for the superposition of the corneal reflection spot on movie film or a television picture of the scene. It provides a ± 1/2 degree accuracy, but strict head fixation is required. The output of the system is graphic, but a 15 x 15 resolving digital unit is available to extract the spot position from a television picture.

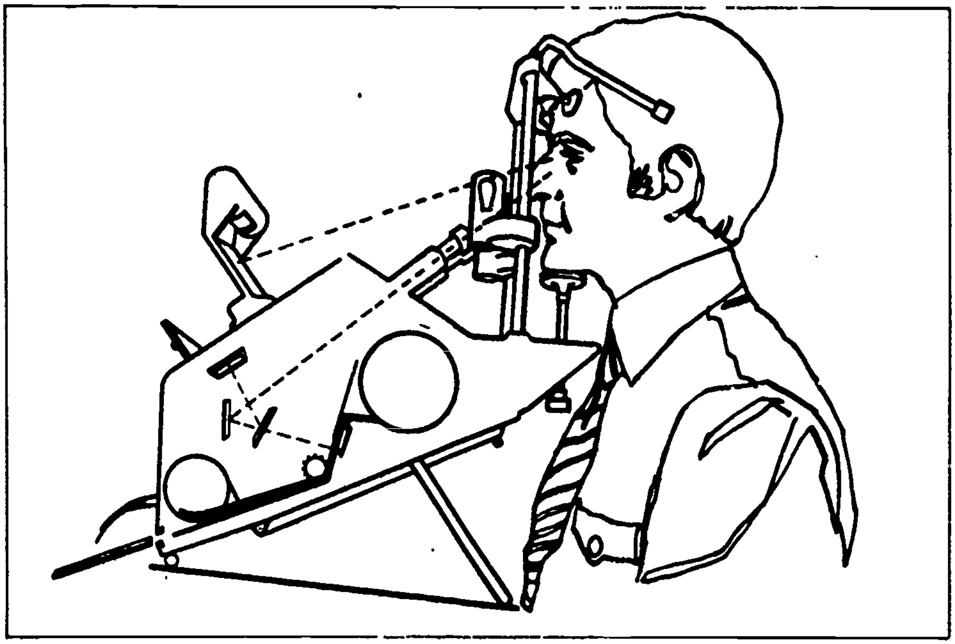


Figure 4.3. The AO Ophtalmograph. (Taylor, 1971) Courtesy of Educational Development Laboratories, A Division of McGraw Hill Book Company

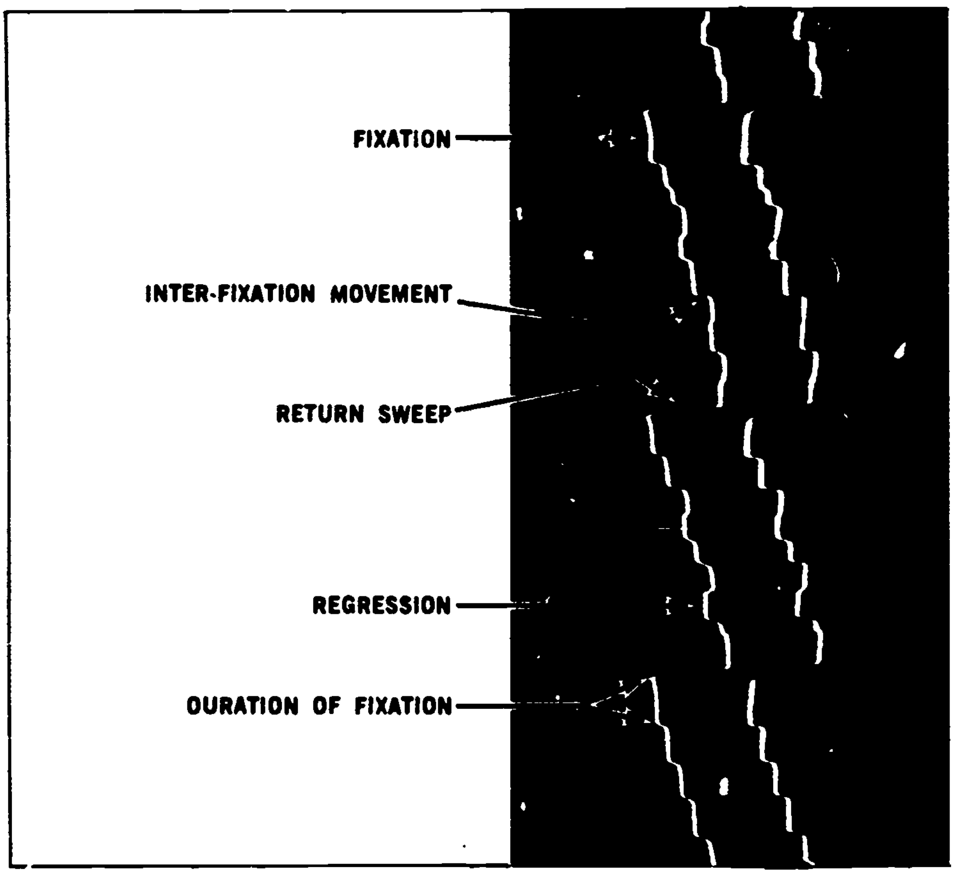


Figure 4.4. Continuous Moving Film Record of Corneal Reflections. (Taylor, 1971) Courtesy of Educational Development Laboratories, A Division of McGraw Hill Book Company

4.2.2.2 Head Mounted Corneal Reflex Camera

An important extension of the basic corneal reflex technique, in which the light source for the corneal reflex is still attached to the head, is the head mounted eye monitor camera. In this free head system developed by Mackworth and Mackworth (1958) a film or television camera, aligned with the head during free head movements, continuously records the field of view. The corneal reflex, measured as a reflected light spot from a peripheral lamp, as in the head fixed system, is combined with the visual field scene through a beam splitter and appears in the film or video display as a white spot placed over the portion of the scene which is being fixated. The system is shown schematically in Figure 4.5. The accuracy is poorer than that with a fixed head system, approximately ± 2 degrees since it s subject to greater error from the relative movements of the light source with respect to the eye associated with head movements. Several commercial versions of the head-mounted Mackworth camera are available. When the camera is mounted directly on the head, as in the early Mackworth helmet mounted camera system, the interference with head movements associated with the weight of the instrument were considerable.

Recent advances have been aimed chiefly at reducing the weight and moment of inertia of the portion of the eye movement recorder which must be worn on the head. Some improvement was made through miniature cameras and miniature TV systems. The largest advance, however, has been the mounting of the camera separately and carrying the visual information, including corneal reflex and the field of view from the head, to the TV or motion picture camera via coherent fiber optics cables. An illustration of one such system is given in Figure 4.6 in which the head piece weight is reduced to 2 pounds. Note that a bite board and head band are used for stabilization.

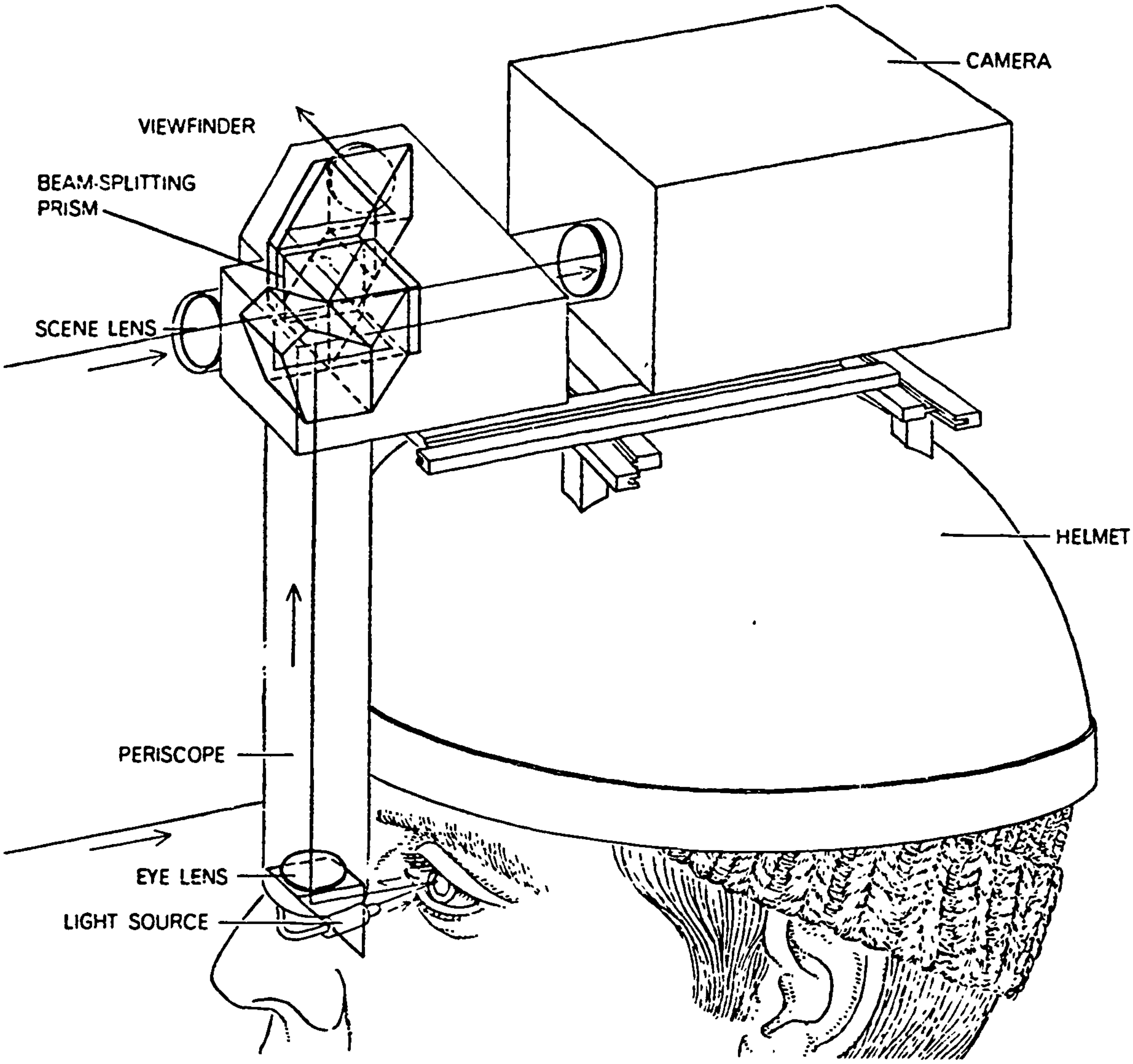


Figure 4.5. EYE-MARKER CAMERA tracks and records the eye's glance. The image of a spot of light, reflected from the cornea, is transmitted by an optical system in the periscope through a series of prisms. This serves to superimpose the eye-marker image on the scene image. The combined image can be monitored through the viewfinder as it is photographed by the motion-picture camera. (Thomas, 1968)

Figure 4.6. Mobile Corneal Reflex Eye Movement Camera. (Courtesy of Polymetric Company).

A similar fiber optics version of the Mackworth camera, manufactured by NAC has a body which weighs less than one pound, with another 5.3 oz for the fiber optics and 9.9 oz for a camera adapter - not carried on the head. This version is pictured in Figure 4.7.

An alternative approach to fiber optics for dropping the weight is the use of a miniature TV camera on the head combining the corneal reflex as before. A picture of such a device and a diagram showing its principles of operation are shown in Figures 4.8 and 4.9. This system, manufactured by NAC of Japan in conjunction with a TV system from Rees Instruments, Ltd. of England requires a combining mirror in the field of view. Its weight is 3 lbs 13 oz with the camera shown, reducable to 15 oz on the head, including cable, with a lighter camera according to specification sheets.

4.2.3 Evaluation of Corneal Reflex Methods

The uncorrected linear range of all corneal reflex systems which employ a single light source for the reflex is limited to eye excursions of ±12-15 degrees vertical or horizontal. Larger excursions place the reflex in the non-spherical and rougher peripheral portion of the cornea and require a complex (usually computer generated) calibration and linearization technique. The reflex range is ultimately limited by the size of the cornea and its partial disappearance behind the lids. In addition to head movements, other factors which limit the accuracy of corneal reflection methods to 0.5 - 1 degree are variations in cornea shape and thickness of tear fluid, corneal astigmatism, and the production of other reflections by eyeglasses (Hall, 1972).

Figure 4.7. Head Mounted Corneal Reflex Illumination, Viewing and Combining Optics. (Courtesy of Instrumentation Marketing Corporation).

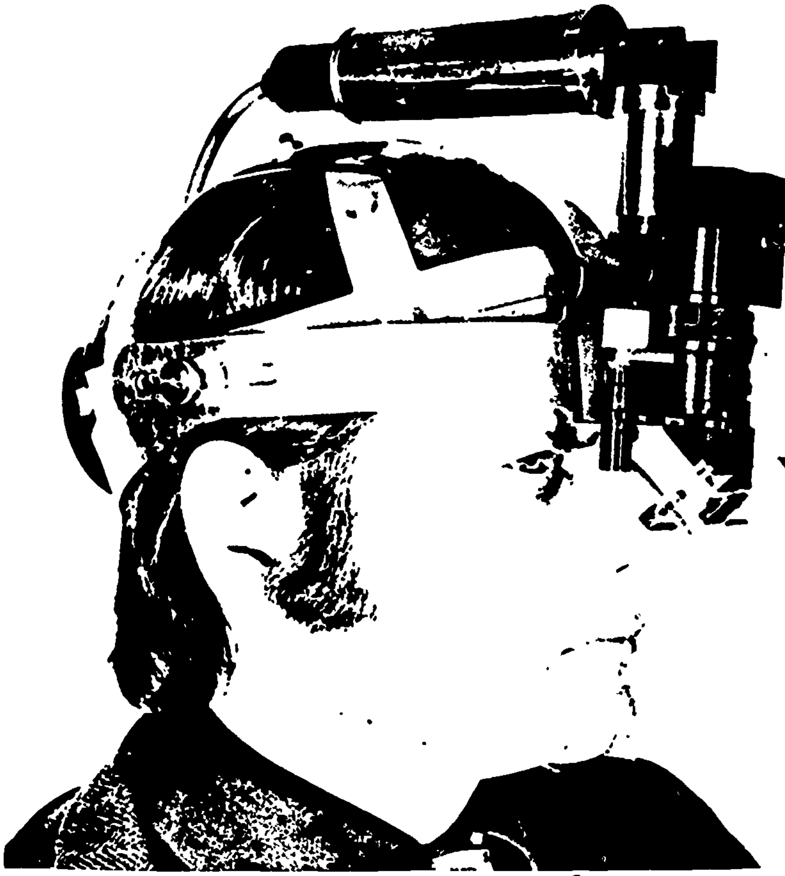


Figure 4.8. Head Mounted Corneal Reflex System with Miniature TV Camera (Courtesy of Rees Instruments, Ltd.)

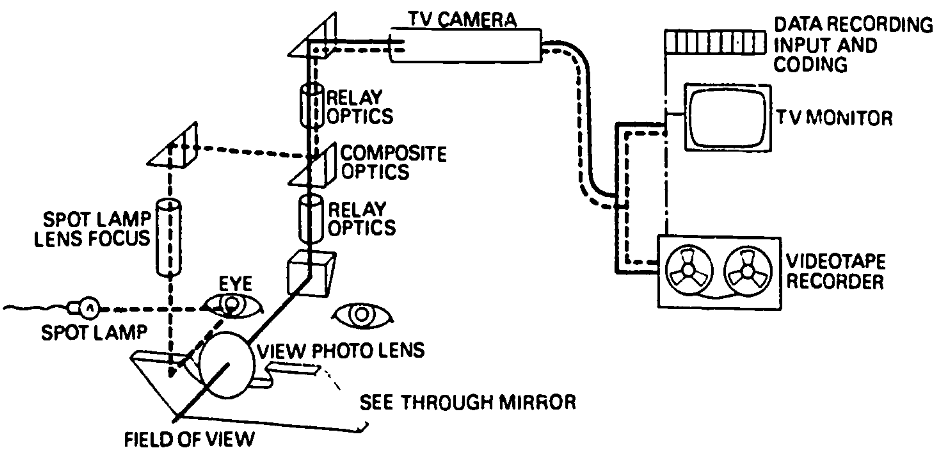


Figure 4.9. Schematic Diagram for Head Mounted TV Corneal Reflex System (Courtesy of Rees Instruments,Ltd.)

The output of most of these systems is usually graphic and therefore requires manual measurement and/or recording. But any of the systems which produce a single bright spot on film or directly on a video signal can be used to provide conversion to the x-y coordinates of that spot. The most common of these converters detects the brightest (or darkest) spot on the video signal and determines its x and y coordinates by the time of its occurence relative to the horizontal and vertical scan sequences. Resolution is about equal to two video lines, or about 1 part in 250 for conventional TV scans. This information can then be digitized for further processing of the part of the field being fixated. Polymetric Co. makes a low resolution digitizer (15 x 15 matrix) for use with their instrument. No other commercial quantitative devices exist for the simple corneal reflex method.

4.3 Limbus, Pupil and Eyelid Tracking

4.3.1 Basic Techniques

The sharp boundary between the iris and the sclera (the limbus) is an easily identifiable edge which can be detected optically and tracked by a variety of means; a human observer looking at the eye can do surprisingly well in determining where the subject is looking. If the entire iris were always visible, and not partially hidden by the lids or orbits, it would be a simple matter to trace its circumference and determine its center. However, because only part of the iris is normally visible, other optical methods, including pupil tracking are necessary to find its center.

When only horizontal eye movements are of concern, then the left and right extremes of the iris can be tracked, either by measuring the gross difference in reflected illumination from fixed areas of the eye on either side of the central gaze position, or by tracking the limbus with a video scan system. When vertical measurement is also required, one may track either the eyelid level, the pupil position, or the vertical motion of a visible part of the limbus. Nearly all limbus tracking systems use invisible, usually infrared, illumination. They all measure the position of the limbus relative to the photodetectors. For head-fixed photodetectors and illuminators, free head movement is possible and the measurement is of eye relative to the head.

The pupil offers a number of distinct advantages over the limbus. First, it is smaller and therefore unobscured by the eyelid for a much greater range of eye motion. For large eye motion, it presents to the observer or the observing instrument a greater portion of the round or slightly elliptical shape. The center of the pupil virtually coincides with the foveal optical axis of the eye. There is a 5.7^{o} deviation between the two, but with most

measurement techniques this can generally be calibrated out. The edge of the pupil is usually a crisper, sharper boundary than that between the sclera and the iris. This makes for a higher resolution measurement.

On the other hand, the pupil, when viewed under normal illumination appears black and therefore presents a lower contract with its surrounding iris than the iris does with respect to the sclera. This makes it a more difficult problem to automatically discriminate the pupil. If collimated illumination is used, however, the light is reflected from the interior of the eye and to an observer looking along the illumination axis, the pupil appears bright. This effect is often seen as "pink eyes" in flash photographs where the flash lamp is close to the camera lens. This phenomenon is employed in the Honeywell Oculometer and other similar devices (Merchant and Morrissette 1974). See Fig. 4.10.

Another characteristic of the pupil which provides both an advantage and a disadvantage is the fact that its diameter varies as a result of both psychological and physiological influences. This makes measuring the center of the pupil somewhat more difficult but it does provide in many techniques the pupil diameter as a collateral output of the measurement which may be of interest to the experimenter in correlating with the position of the eye at any point in time.

4.3.2 Specific Implementations

4.3.2.1 Scanning Methods.

One technique involves scanning of the eye with a normal TV camera, which has sufficient sensitivity in the near infra-red region (700 - 900 mμ) to be effective with IR lighting. Horizontal sweeps which intersect the iris and the pupil have a video signal as shown schematically in Figure 4.11. The horizontal position of the limbus or the pupil is determined by the horizontal sweep of the line crossing the center of the iris with video contrast very high.

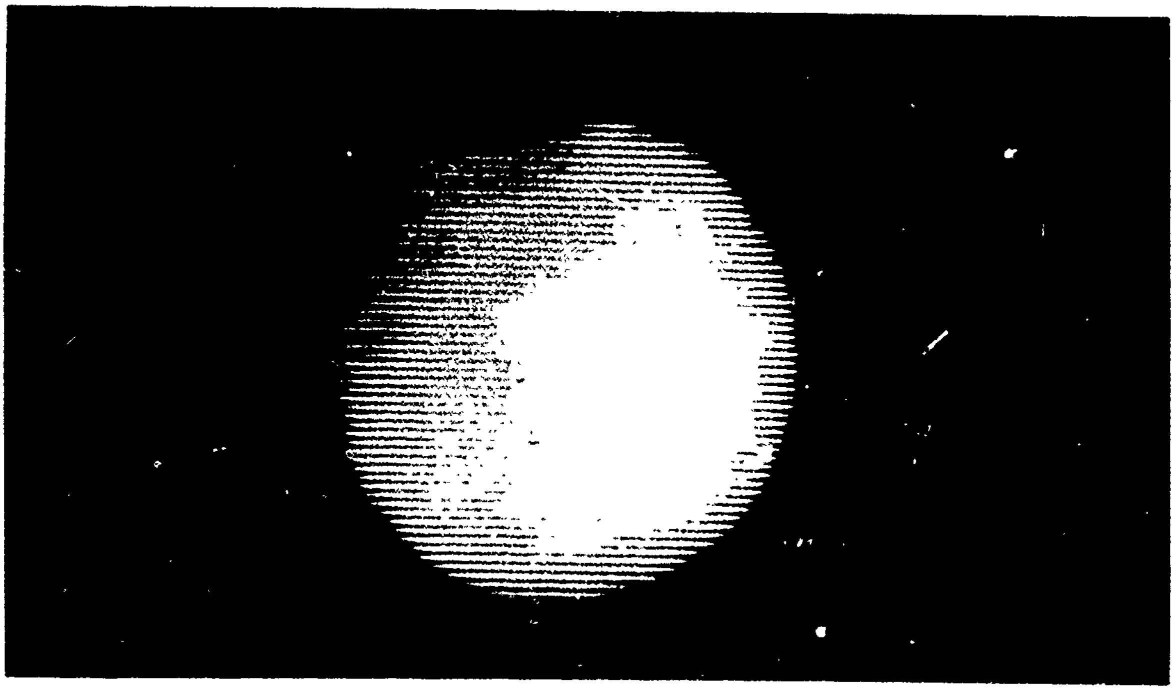


Figure 4.10. TV Picture of a Bright Pupil.
(Merchant and Morrissette, 1974).

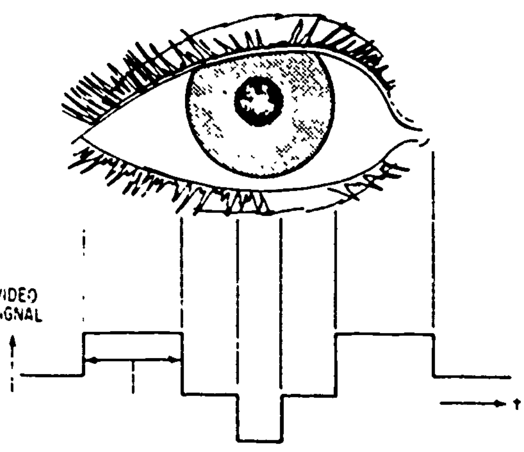


Figure 4.11. Scanning Method for Tracking Limbus. (From "Recording Eye Position," Biomedical Engineering Systems, Clynes & Milsum ed. Copyright 1970, McGraw Hill Book Company. Used with permission of McGraw Hill Book Company.

The time from the start of the sweep to the drop in intensity at the first iris boundary is a measure of the eye horizontal position relative to the camera. Since the total sweep time is 62 microseconds, resolution of 1/500 of the line length (comparable to vertical resolution) requires circuitry to give time resolution of 0.1 microseconds, which is now within the state of the art. Choice of which line is to be measured can be done in two ways. One is to measure the left iris boundary every sweep, and select the one which is furthest to the left as the mid-line. The other method is to rely upon the vertical eye position measurement to select that horizontal sweep which crosses the center. For example, measuring the top and bottom sweeps which intersect the pupil, yields pupil diameter as well as vertical pupil position. That line which is mid-way between the pupil top and bottom can be selected as the mid-line and its intersection with the pupil or iris measured (Sheena, 1973). See Figure 4.29. Vertical resolution is limited by scan line density. For standard US systems this yields, at best, 1 part in 212 per field (2 fields/frame) at a 30 Hz rate or 1 part in 525 at a 60 Hz rate. Horizontal measurement of the pupil boundary has to take into account the varying pupil diameter.

Other methods of scanning have been applied to tracking the limbus or the pupil. A programmable video scan, or image dissector can be used to trace the circumference of the pupil for determination of the center (Merchant, 1969) or to trace only the visible portion of the curve of the limbus and from that information calculate the coordinates of its centroid (Sheena, 1969). This latter method permits large eye excursions. Instead of illuminating the eye uniformly and tracking with a wide scan, one can scan a small spot of light across the eye and measure the return reflected light at every instant. Cornsweet (1958) used such a flying spot scanner to track the limbus. Rashbass (1960) used it to maintain a small sweep tangent to the limbus at a fixed angular orientation, thus measuring the vertical and horizontal eye position from tracking a single part of the limbus. See Figure 4.12.

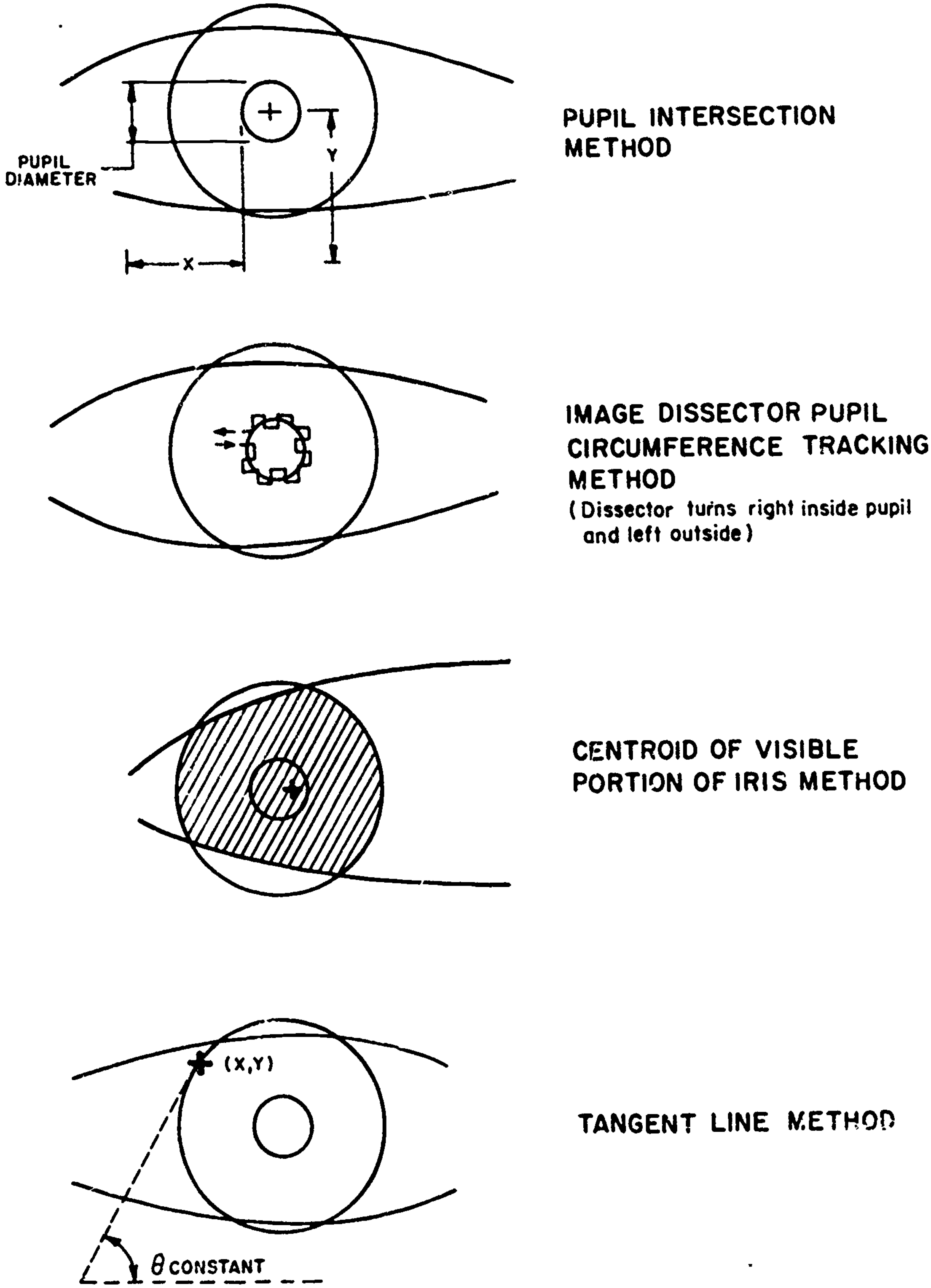


Figure 4.12. Various Scan Methods Applied to Tracking the Limbus and Pupil

A TV camera with an image dissector has been applied to precise tracking of the corneal reflex (Ishikawa et al, 1971). The main horizontal sweep is a normal full picture left to right scan, which is used for approximate location of the bright reflex, whereas every second sweep is a short (high resolution) line centered in the part of the field containing the reflex. This combination scan of coarse slow and fine rapid sweeps was used to track vertical and horizontal eye movements over the range of $\pm$ 15 degrees with a resolution of 0.01 degrees and frequency up to 15 KHz.

4.3.2.2 Differential Reflection Methods

Scanning methods involve fixing the head or the weight of a TV, other scan mechanism or the fiber optic connections from a head-mounted device. Similar results can be obtained by measuring limbus position with two or more small photocells viewing appropriate parts of the eye, either directly or examining its image. Just as with the scanning systems, there are basically two choices - either broad illumination and tightly constrained fields for photodetection or the use of focused slits or circles of light on the eye with relatively large detection regions. Each of these methods is used, although the most common uses broad field illumination so that only one source and no mask is required.

In the earliest versions of this device, Torok et al (1951) and Smith and Warter (1960) imaged one side of the eye on a small horizontal slit placed in front of a photomultiplier. As the eye moved horizontally, the image on the slit contained more or less bright sclera, depending on the direction of eye movement, and thus the photocell output varied. Accuracies of 15 arc minutes over several degrees were obtained with careful head restraint. A current commercial version of this technique is shown in Figure 4.13. This tracks the horizontal movement of each eye by recording differences in output of two photocells on opposite sides of the iris image. All of these methods require a fixed head and a fixed place for

Figure 4.13. Differential Reflection Reading Eye Movement Measurement Device. (Courtesy of Biometrics Division, Narco Bio-Systems, Inc.)

reading material. Richter (1956) placed the light and photocells on goggles worn by the subject, and relied on diffuse reflected light from the sclera rather than an image. Stark and Sandberg (1961) use. two small lamps illuminating small discs on the two sides of the iris, and recorded the difference in reflected light from two photocells viewing these areas. (See Figure 4.14.) The two cells permit a larger range of horizontal eye movement (to ±15 degrees), a more linear relationship than a single sensor, and relative insensitivity to vertical movements because of the push-pull sensor arrangement. With photodiodes attached to a spectacle frame, accuracy is over the order of 15-30 arc minutes. When the head is rigidly held in place with a bite board, and narrow beam photodiodes used with a range of a few degrees, resolution of 10 arc second is possible (Zuber, 1965). The interference of any changes in ambiant illumination is now overcome in most systems by illuminating the eye with chopped light, and then demodulating at the same frequency. Chopper wheels in the light path are useful in immobile systems (Wheeless et al, 1966), but infra-red light emitting diodes (GaAs) are small and preferable for monitors which are built on spectacle frames to allow free head movement (Young, 1970), as seen in Figure 4.15. Findlay (1974) used a bifurcated fiber optic bundle to both illuminate the limbus and to collect the reflected light as shown in Fig. 4.16. In this manner both light source and detector are effectively placed closer to the eye resulting in a smaller illuminated area sensed by the detector.

Measurement of the vertical position with the differential reflection methods is difficult, for the same reasons as with scanning techniques. For this purpose, Young tracked the upper lid position with the output of two photodiodes arranged to be relatively insensitive to horizontal motion. A new variation on this method by Mitrani et al (1972) uses a third photocell and a separate light source to measure the vertical eye movements by tracking the related lower lid height. As seen in Figure 4.17 the light from this source falls directly on the additional photocell, partially shadowed by

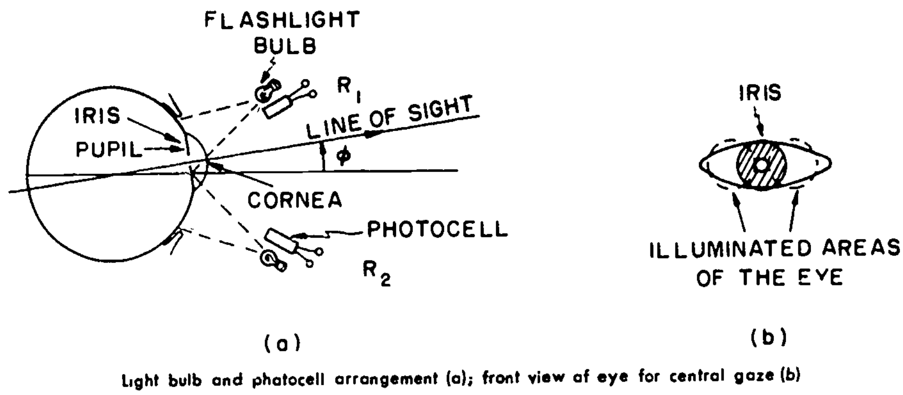


Figure 4.14. Light and Photocell Arrangement for Limbus Tracking. (Stark et al., 1962).

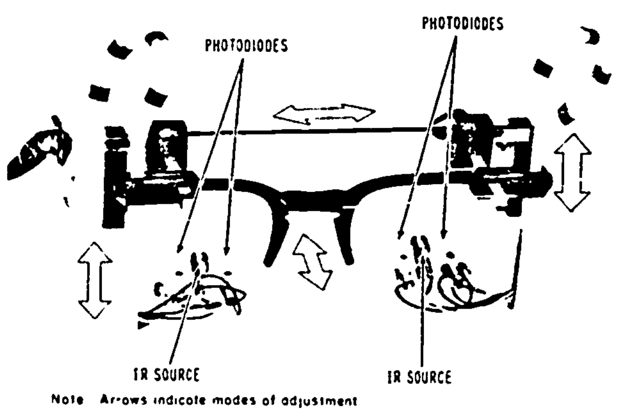


Figure 4.15. Spectacle Mounted Differential Reflectivity Device. (Courtesy of Biometrics Division, Narco Bio-Systems, Inc.).

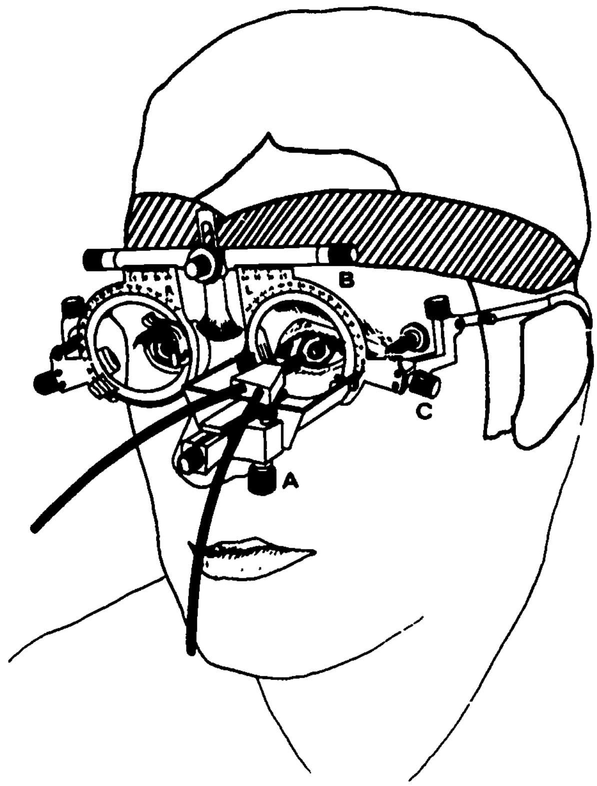


Figure 4.16. Limbus Tracking with Bifurcated Fiber Optics. (Findlay, 1974).

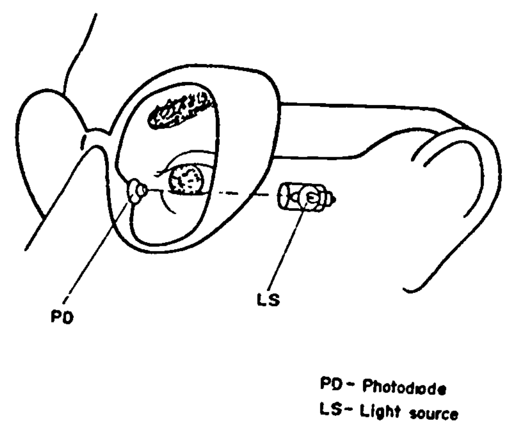


Figure 4.17. Tracking of the Lower Lid. (Mitrani, et al., 1972).

the lower lid. Although linearity is a problem for large eye movements, resolution of 15 arc minutes, comparable to the horizontal, is reported.

Finally, the differential reflection technique can be extended to measurement of vertical eye movement by the proper positioning of the viewing areas or the use of additional areas. Wheeless et al (1966), in an immobile system with the head fixed using a bite board, brought an image of the eye onto two detectors, which could be arranged for horizontal or vertical recording. The eye illumination, coming from a chopped source, was brought to the eye with four fiber optic bundles and their projection lenses, as shown in Figure 4.18. The eye viewed through a beam splitter with visible illumination is imaged on a frosted screen. The four fiber bundles are then manipulated to yield the pattern of four slits on the eye seen in Figure 4.19, and the infra-red filter is replaced for recording. The difference between the iris-pupil detectors 3 and 4 is a measure of vertical eye position, independent of pupil diameter to first order. Another variation described by Jones (1973) uses only two photocells. Using very short focal length lenses (12 mm) and rectangular masks in front of each photocell, he projects 3.8 x 0.5 mm strips of photocell fields onto the lower limbus in the orientation shown in Figure 4.20. Horizontal eye motion effects the light sensed by the two photocells differentially, while vertical motion changes them similarly. By separately adding and subtracting the two photocell outputs, a monotonic, though nonlinear measure of vertical and horizontal eye position is achieved with a simple, light spectacle mounted device.

4.3.3 Evaluation of Limbus and Pupil Tracking Techniques

Many implementation of these techniques yield good results with good accuracies for a reasonable range. The output is an electrical record which can have a good frequency response.

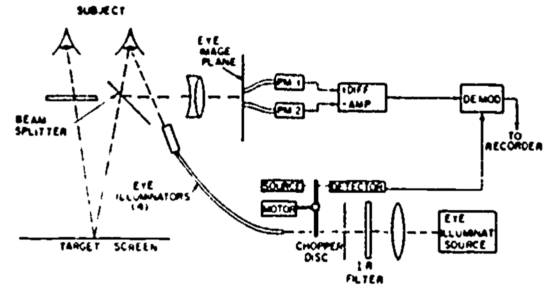
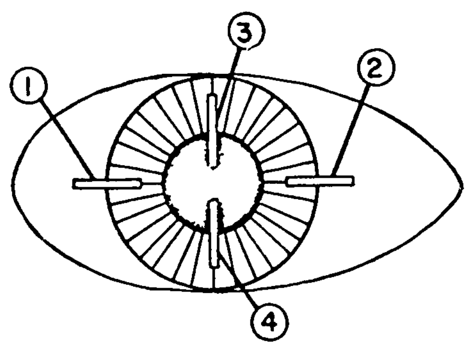


Figure 4.18. Tracking of Limbus Image. (Wheeless, et al., 1966).



Position of detector fiber bundles on eye image. Areas 1 and 2 are used for horizontal-motion detection, 3 and 4 for vertical motion detection.

Figure 4.19. Position of Detector Fiber Bundles on Eye Image. (Wheeless, et al., 1966).

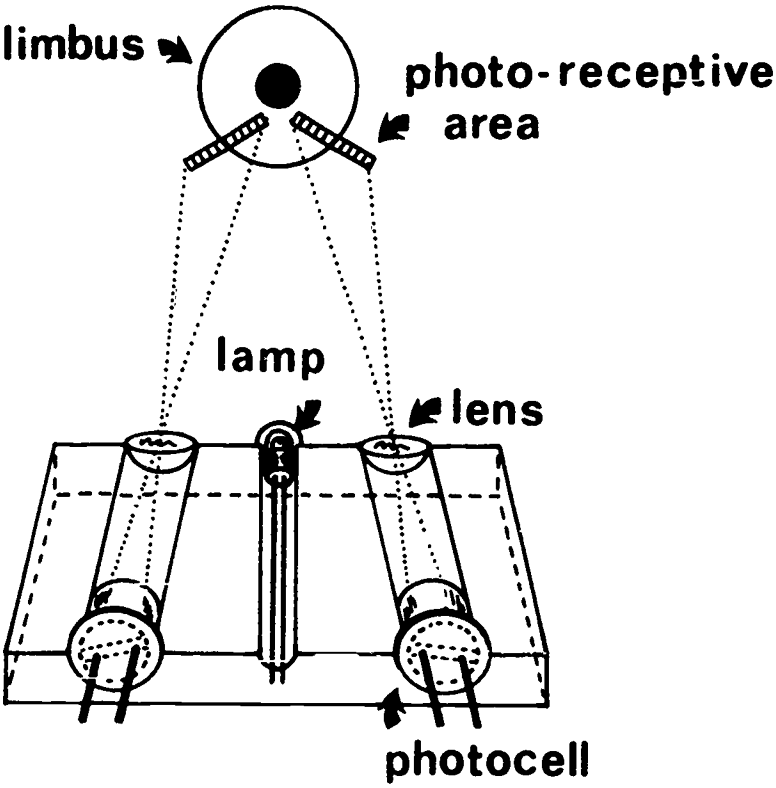


Figure 4.20. Illumination Pattern for Two-Dimensional Limbus Tracking. (Jones, 1973).

As noted, however, vertical eye movements are a problem. The technique also requires head fixing or a head mounted device. The latter can be quite light but precludes eyeglasses. Iris coloration can also be a factor in its utilization.

4.4 CONTACT LENS METHOD

4.4.1 Basic Techniques

The most precise measurements of eye movement are made with one of the techniques employing some device tightly attached to the eye with a contact lens (Ditchborn and Ginsborg, 1953; Riggs et al, 1953; Yarbus, 1967 for example). Conventional corneal lenses are too mobile to be of use, and all measurement systems use special lenses consisting of two individually ground spherical surfaces to fit snugly over the cornea and sclera. For accurate recording it is essential for the lens to move with the eye - both in steady displacement and during the high acceleration associated with voluntary saccades. Tight fit and lack of slip is achieved by close grinding tolerances and by the suction effect of 20 mm Hg or more negative pressure between the contact lens and the eye. Fender (1964) pointed out one way of developing the negative pressure by filling the cavity with a 2% sodium bicarbonate solution which osmoses out through the tissue. Yarbus (1967) achieved the accurate tracking required for image stabilization work by withdrawing a small amount of fluid through a valve after applying the lens. Withdrawing air from under the contact lens is also effective for stabilization, but of limited time use because of the lack of corneal irrigation. All of the contact lens systems cause discomfort, and the very tight ones usually require the application of a topical anesthetic. Fender (1964) estimates that even with the best current stabilization, the lens slips behind the eye about 1 arc min during a 1 degree saccade, and 6 arc min during a 9° saccade. The contact lens and its associated attached material should not be of a size or mass to interfere with normal eye movements. Those which include a protruding stalk preclude normal blinking.

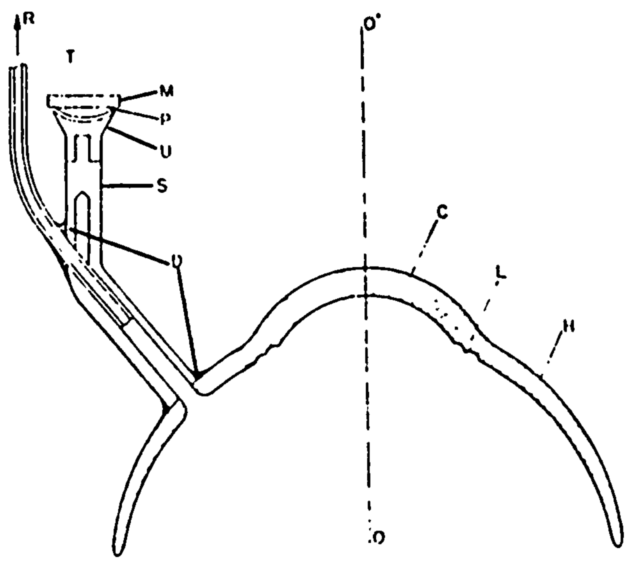
4.4.2 Specific Implementations

The most commonly used contact lens system is the "optical lever", in which one or more plane mirror surfaces ground on the lens reflect light from a light source to a photographic plate or photocell or quadrant detector array. (The latter is a solid state photodetector arrangement which produces a pair of voltages proportional to the x and y coordinates of a spot of light falling on the sensitive area. It is used in the double Purkinje image method discussed below.) The reflection from a plane mirror has a number of accuracy advantages over the corneal reflection techniques. First and least important of all, for the plane contact lens mirror the change in reflection angle is twice the eye rotation angle rather than 1.3 times as large. Second, the imperfections related to the cornea are eliminated. Most important, however, is the fact that the angle of reflection depends only on eye rotation and is independent of pure linear displacement, as long as the incident beam still illuminates the mirror. This fact makes the system largely unaffected by the inevitable small head movements which interfere with corneal reflection methods. Collimated light is reflected from such a plane mirror and focused with a lens on an image plane. When the eye moves, lateral motion of a plane mirror in a collimated beam does not cause a shift in image position. Only rotation of the eye and the mirror will produce deflections of the projected image (Ratliff and Riggs, 1950). Nevertheless, because of the high inherent accuracy of the system, very careful head stabilization relative to the recording device is usually used.

One early version of the optical lever principle, by Ditchburn and Ginsborg (1953) used a 3 mm diameter optical plate on the lens 35^{o} off the visual axis to reflect a slit of light through a cylindrical lens camera to moving film for a record. The orientation of the slit and of the camera determined whether horizontal or vertical eye movements were recorded. Movements as small as 5 arc seconds can be recorded with the

optical lever, over a range of $\pm 5^{\circ}$. The frequency response of the system is generally determined by the stability of the lens in following the eye and by the recorder response. When the plane of the mirror is not normal to the visual axis, torsional movements of the eye also effect the reflected beam angle. Matin and Pearce (1964) used this fact to advantage and embedded two mirrors into the contact lens, one temporal and one nasal, so that the reflected beams move in opposite directions during ocular torsion. By resolving the beam deflections from an eye movement into orthogonal rotations about the original axes with an analog computer, they were able to measure 3 axis rotations to within 2 arc seconds.

Those techniques using flush, embedded mirrors suffer from changes in mirror properties with tear film, especially when the output is measured photoelectrically rather than photographically. For that reason several contact lens optical mirror systems employ mirrors or lights mounted on stalks projecting from the lens. Fender (1964), in one version, attached a single mirror to the end of a stalk for two axis recording and at other times used orthogonal mirrors for 3 axis measurement. Construction details of one Haptic contact lens unit with a stalk/mirror are shown in Figure 4.21. A small light, weighing less than 50 mg has also been mounted at the end of a contact lens stalk parallel to the visual axis to throw a moving shadow across a photomultiplier face for accurate recording of horizontal or vertical miniature eye movements (Byford, 1962). Byford shows that his aluminum stalk and lamp assembly had mechanical resonance peaks at greater than 200 Hz (the one chosen was at 350 Hz) and were adequate for the calculated 150 Hz bandwidth required for miniature saccade displacement recording. Further tests using a 1/8 inch o.d. hollow perspex stalk showed it to have a high enough resonance peak for satisfactory use for retinal image stabilization. One way of creating a small light source



Haptic contact lens with stalk/mirror unit attached. O-O' optical axis; R to suction reservoir; T polyethylene tube 1/16 in.o.d.; M flat front surface mirror; P grease pad (M may be moved laterally on P for collimation purposes); S stalk 1/8 in.o.d., drilled bore 1/16 in. i.d., to allow entry of suction tube T; C corneal section of lens; L transcurves over limbus; H haptic section; D Durofix seals; U cup.

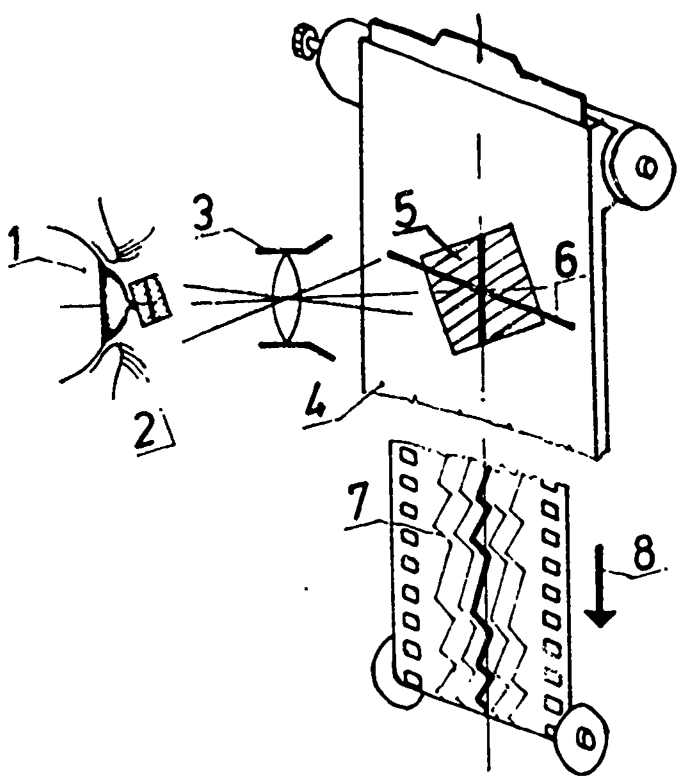
Figure 4.21. Plane Mirror Attached to Scleral Lens. (Boyce and West, 1968).

on the contact lens without a lamp and its associated power leads, and thereby permitting lid closure, is by using a small radiating source. Nayrac et al (1969) placed a small bit of the luminescent phosphor containing radioactive tritium on the contact lens. The 1 mm^2 surface glowed brightly under ultraviolet illumination. The position of the spot and thus the eye, was monitored in two axes by use of two optical density wedges, placed in front of separate photomultipliers for recording horizontal and vertical motions. They report a resolution of 20 arc minutes, which is poor for a contact lens system, but a useful range of 0.3 to 30 degrees.

A recent addition to the repertoire of optical contact lens methods is one in which a multiple line pattern, fixed to the contact lens stalk, is imaged through a slit on moving film, as shown in Figure 4.22. The film pattern of one thick and several thin lines shown schematically in Fig. 4.23 contains all the information needed for measurement of vertical, horizontal and torsional eye movements as a function of time.

The principal non-optical contact lens measuring method is the search coil technique introduced by Robinson (1963). Two small wire coils, oriented perpendicular to each other and embedded in the contact lens, pick up an induced voltage from two large perpendicular electromagnetic coils surrounding the subject. The induced voltage in each coil varies only with the sine of the eye angle relative to the magnetic field, and is independent of head position within the uniform portion of the field. Use of different frequencies or quadrature phases in the two large coils permits the detection of the angle between each search coil and each driving plane, and therefore stable three dimensional angular localization to the order of one arc minute over large angular excursions. Voltages are read out through light flexible wires extending from the lens. Extension of this technique to implanting the coils on the globe for chronic animal experiments permit the precise repeatable localization of eye position.

Figure 4.22. Line Diagram Fixed to the Eyeball by Means of the Scleral Contact Lens. (Forgacs, et al., 1973).



The modified photonystagmographic method of Forgács.

When properly set, on the surface of the film cassette facing the lens (4) of a special camera (3)—provided with 0·1 mm. wide transversal slit (6)—the magnified, sharp picture (5) of the line diagram fixed to the eyeball (1) by means of the scleral contact lens (2) is obtained. This picture is crossed by the transversal slit (6). The thick line of the line drawing is perpendicular to the slit, while the thin lines intersect it at an angle of 30°. On the film moving downwards (8) in the cassette behind the transversal slit at a constant speed of 10 mm./sec., curves in a number corresponding to the number of points of intersection between the lines of the diagram and the transversal slit are depicted as the eye moves. This set of curves makes up the photonystagmogram (7).

Figure 4.23. The Modified Photonystagmographic Method of Forgács. (Forgacs, et al., 1973).

4.4.3 Evaluation of Contact Lens Methods

Although the contact lens systems offer the best resolution of any system down to 5-10 arc seconds, they do so in general at the sacrifice of range. They are normally applicable for the study of miniature eye movements and, with the exception of the magnetic search coil method, are inappropriate for movements of greater than 5 degrees. The expense and discomfort of the contact lens makes it a technique more suitable for use on a few subjects for physiological studies of fixation than for wide-spread investigation of reading.

The dangers of fitting a contact lens with negative pressure are also considerable. There is the possibility of deforming the cornea and the worse hazard of damaging the accommodation muscles as a result of the pressure stress placed upon them.

4.5 Point of Regard Measurement: Tracking of Corneal Reflection Center with Respect to the Pupil Center

4.5.1 General Principle

It is often of interest to the investigator to know the fixation point of the subject as it falls in space rather than the position of the eye with respect to the head. In other words, one wants to determine where a subject is looking regardless of whether his eye got there through eye rotation or head motion. Clearly the two measurements are equivalent if the head is fixed, or the position of the head may be measured by any of a number of techniques and the position of the eye in space deduced by summing the relative position of the eye to the position of the head. Various head position measurement techniques will be discussed in Section 4.8.

One of the main problems of measuring eye direction optically is that of separating lateral motion of the eye relative to the observer or the sensor and rotary motion of the eye relative to the scene. For example, eye rotation can be measured by tracking the corneal reflection of a suitable source, however, it is not possible to distinguish of motion of the corneal reflection which results

from rotation or translation. Unless the corneal reflection tracker is the head-mounted variety described in a previous section, lateral motion of the head will introduce large errors approximately 1° of error for every 5×10^{-3} inches of lateral head motion. It is difficult to eliminate this head motion completely by any fixing methods.

A desirable method is one which would allow relatively free, natural head motion and measure the position of some parameters of the eye in such a manner that they would indicate eye rotation only and consequently point of gaze in space. This may be done by measuring features of the eye which only change with rotation or by measuring the positions of various details on the eye which move differently as a function of head motion and eye rotation such that pure eye rotation can be deduced from them. Two features which satisfy this requirement are the corneal reflection and the center of the pupil. Each has been independently used for eye position determination but differentially they provide a powerful tool.

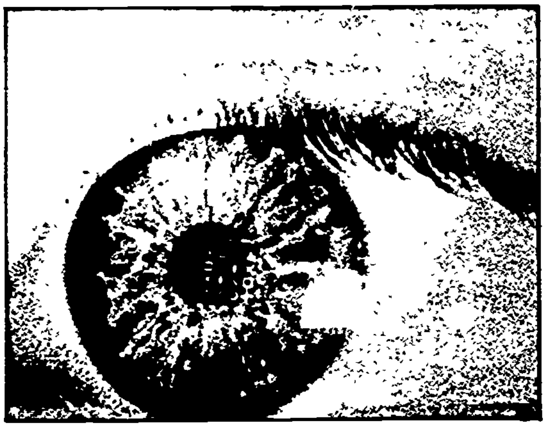
4.5.2 Specific Implementations

The corneal reflex was discussed at length in a previous section. It possesses a very useful property. If a subject is looking directly at a light source, and an observer is looking at the subject's eye from a position at or very near the light source, then, from the obvious considerations of symmetry the corneal reflex will appear to the observer to be in the center of the subject's pupil. This result may be used in either of two ways. First, the image of the point on which the subject is fixating will be found in the center of the pupil. Second, the subject's point of regard with respect to the light source is approximately proportional to the distance between the image of the light source and the center of his pupil. These two properties are equivalent to each other. In the first, the light source is moved and the extent of this motion is effectively measured. In the second, the light source is not moved and the error between its image and the center of the pupil is

measured. Both results are monotonically related to the point of regard. Measurement of the center of the corneal reflection from the limbus is also possible, but poses practical problems.

Both these approaches are applied to methods of eye point of regard measurement. The first is effectively the inverse of the conventional corneal reflex method where the reflections were superimposed on the scene being viewed by the subject, and the eye position is determined by where the corneal reflection falls on the scene. In the Wide Angle Mackworth Camera, the illuminated scene is itself used as the light source for the reflection. By photographing the eye at high magnification, the corneal curvature produces a superimposed image of the field being viewed, with the position "being" fixated lying directly in the center of the pupil. See Fig. 4.24. Since the entire field is being imaged over the small area of the cornea, resolution is lost relative to the simple corneal reflex method. This method is therefore not very amenable to high resolution analysis. Also, in orde. to photograph a scene reflected from the cornea, the field must contain bright li _ sources against dark backgrouns. It does, however, provide a method of obtaining eye fixation points without excessive head restraint requirements. All that is required is that the pupil center be visible to the observer or the observing instrument.

A commercial instrument exists which performs this type of measurement, The Polymetric Company Wide Angle Eye Movement Recorder. It outputs a photograph (Fig. 4.24) from which fixation may be determined, or a 4 x 4 digital position output provided with a television system. It offers a 40° maximum field of view, $\pm$ 2.5 recording accuracy when manual determination is made and a 1 part in 4 electronic accuracy. The sampling rate is 12 photographic frames per second or 60 TV fields per second. The system requires no bite board. The subject looks at the scene through a viewing aperture.



Eye of two-year-old child.
Fixation on small square.
Four-sided grid marker used.
Stimulus material is
rear-illuminated transparency.

Figure 4.24. Photograph from Wide Angle Mackworth Camera. (Courtesy Polymetric Co.).

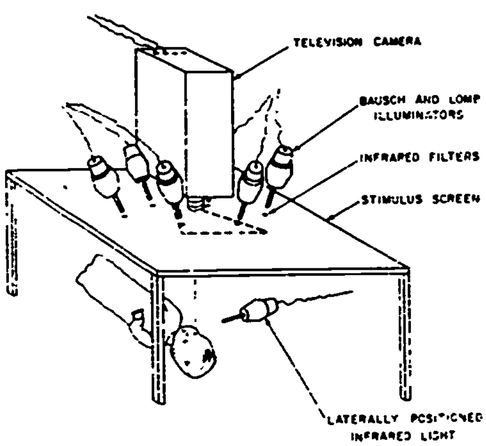


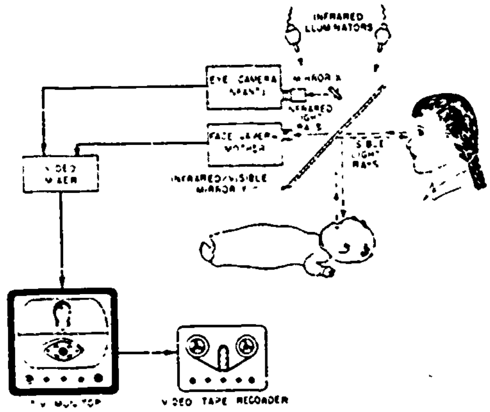
Illustration of a system for recording eye behavior in infants. (A television camera, infrared lights, a stimulus screen, and a baby are shown.)

Figure 4.25. Illustration of a System for Recording Eye Behavior in Infants. (Haith, 1969)(Copyright (1969) by the American Psychological Assn. Reprinted by Permission).

In another application of the wide angle corneal reflex technique using multiple light sources, Salapatek and Kessen (1966) and later, Haith (1969) developed a wide angle corneal reflex technique for use with the human infant. The arrangement of fixed infra-red illuminators over the infant's head is shown in Figure 4.25. The TV picture of the eye contains the corneal reflex of some or all of the six infra-red illuminators ; scoring is done using video tape on a frame by frame basis.

The x-y coordinates of the pupil center and of a particular infrared reflection are measured with a curser whose position is outlined by a superimposed cross on the video monitor. By use of a video mixing system, a second TV picture can be added to the first so that each frame contains both eye position and a picture of the field being scanned, as shown in Figure 4.26.

The wide angle Mackworth camera uses what effectively is a wide field corneal reflex and determines which part of it appears in the center of the pupil. A second version of this method is to use a single point corneal reflex and to find how far it lies from the center of the pupil. This principle was put into practice by the Oculometer developed by Merchant (1969) at Honeywell. In the Oculometer a single light source is used to produce corneal reflex on the pupil. The problem of obtaining net eye motion with respect to the scene is overcome through the tracking of two elements of the eye that move differently with eye position and head position. As discussed above, the pupil is viewed by observing optics that are coaxial with the illumination optics in the Oculometer. The corneal reflection appears always in line with the center of corneal curvature. The apparent displacement of corneal reflection from the center of the pupil is thus equivalent to the apparent displacement of the center of corneal curvature from the center of the pupil which is obviously a function of eye rotation only. See Figure 4.27 (Merchant and Morrissette, 1973). This phenomenon may be graphically seen from Figure 4.28 which shows that the corneal reflection with respect to the center of pupil position remains unchanged as a result of lateral head motion and changes for eye rotation only.



An illustration of a procedure for recording eye-to-eye contact between mother and child. (A mirror at a 45-degree angle to the visual axes of the mother and the baby reflects visible light thus producing an apparent natural vis-à-vis image to both. The infrared image of the infant's eye is transmitted through Mirror Y, reflected by Mirror X, and then recorded by the top television eye camera The infrared image of the mother's face is transmitted by Mirror Y and recorded by the lower television face camera. The outputs from these two cameras are mixed into one picture and then recorded onto video tape.)

Figure 4.26. An Illustration of a Procedure for Recording Eye-to-Eye Contact between Mother and Child. (Haith, 1969)(Copyright (1969) by the American Psychological Association. Reprinted by Permission).

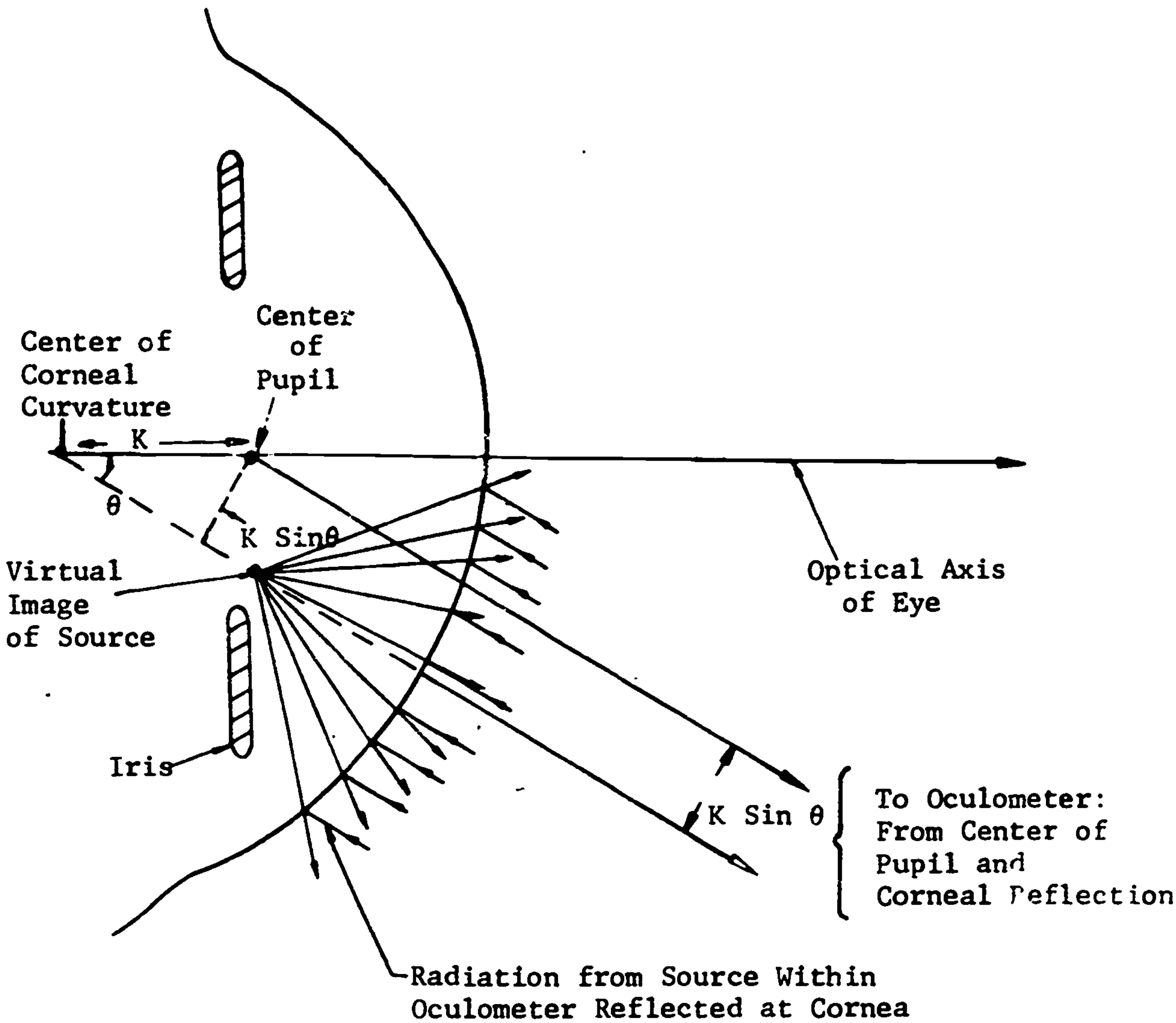
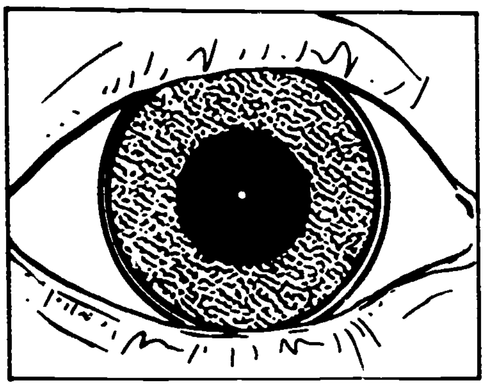
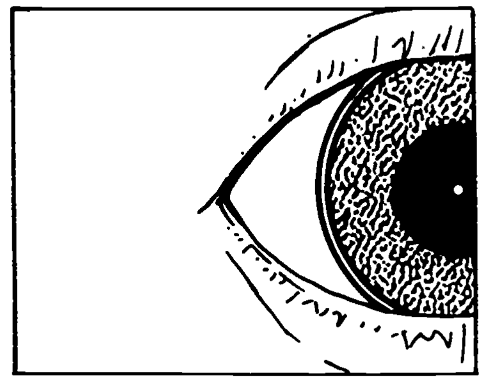


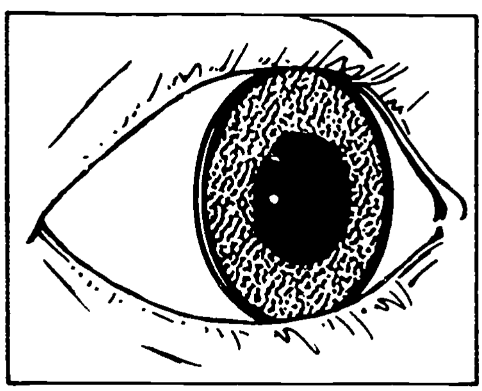
Figure 4.27. Displacement of corneal reflection from center of pupil, K Sin θ, is proportional to the angular direction, θ, of the eye, and is independent of the position of the eye. (Merchant and Morrissette, 1974).



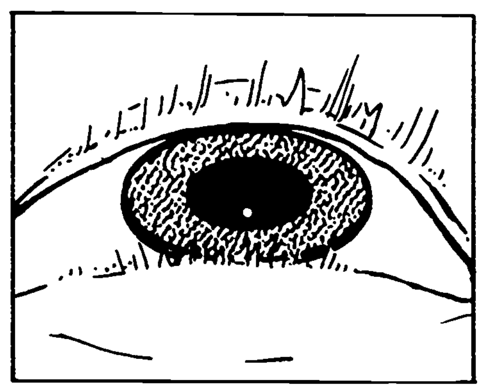
(a)



(b)



(c)



(d)

(a) Eye looking straight ahead - note corneal reflection is at center of pupil.

(b) Eye looking straight ahead but laterally displaced - note corneal reflection still at center of pupil.

(c) Eye looking to side - corneal reflection displaced horizontally from pupil center.

(d) Eye looking up - corneal reflection displaced vertically from the pupil center.

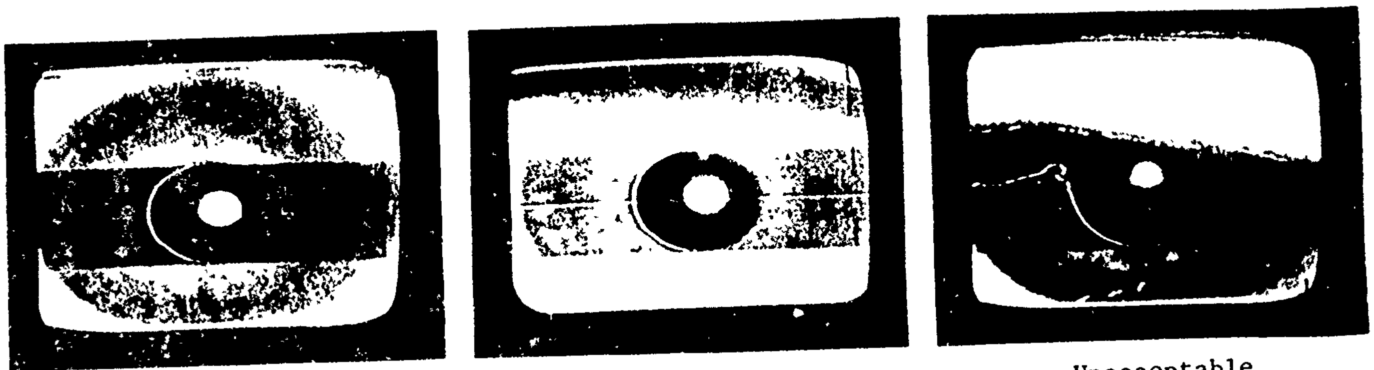
Figure 4.28. Effects of Eye Translation and Rotation on Corneal Reflection - Pupil Center (Merchant and Morrissette, 1974)

A number of versions of this instrument exist which automatically find the pupil center and corneal highlight in the x-y plane and calculate eye position from the relative vector. These include the Honeywell Oculometer,(Merchant and Morrissette,1973), a portable Oculometer for transporation studies developed at the Department of Transportation (Davis, 1971), the EG&G/Human Engineering Laboratory facility (Hall, 1973 ;Monty, 1975), a laboratory Oculometer developed by the University of Alberta (Petruk, 1974) and the Whittaker Corporation Eye View Monitor (Sheena, 1973).

Several techniques are available to present a non-visible light source to develop the corneal reflection and to locate the pupil center and corneal reflex on the image. Honeywell and Whittaker use an invisible infra-red light source for the corneal reflection and use a TV camera with sufficient sensitivity in the infra-red region to detect this highlight easily. EG&G in their original version used visible light. By having all of the light sources in the room polarized except for a small portion by passing all returned light through another polarizing filter to a low light level TV camera, the corneal highlight was sharply defined.

With the Honeywell Oculometer and others, the pupil is backlighted and the resulting image is the bright pupil and even brighter corneal reflex as in Figure 4.10. In some Whittaker units, and the EG&G/Human Engineering Laboratories system, the pupil is black as is Figure 4.29.

The center of the pupil was determined in Merchant's original design by an image dissector which traced the circumference of the pupil and tracked it as it moved. As with any image dissector tracking system, this required some time for reacquisition of the pupil whenever it was lost, as for example during a blink. However, currently, all of the systems appear to use a conventional TV raster system in which the geometrical coordinates of the pupil center and of the high light are determined by timing signals on the video scan. For example, if the corneal reflex corresponds to the brightest point in the picture, and it was located in the upper left hand portion of the picture a quarter of the way down from the top and a quarter of the way in from the left, the highest voltage on



Acceptable | Acceptable | Unacceptable

Figure 4.29. Operator Indicators Superimposed on TV Image of Eye as a Function of Threshold Setting Showing Status of Measurement. Measurement is Good when Pupil is Properly Delimited. (Courtesy Whittaker Corporation).

the video scan would occur 25% of the time from the beginning of a new field following the vertical sync, and 25% of the time across a horizontal scan line. A variety of processing and pattern recognition aids in determining the center of the pupil and corneal reflection correctly have been developed in connection with video systems. Indicators are also superimposed on the video as operator aids; see Figure 4.29 (Sheena, 1976). A Silicon vidicon television system is also generally used for its high sensitivity especially in the IR region.

The most advanced Honeywell Oculometer can follow large head motion by maintaining a field of view which covers the subject's eye by driving a two axis mirror which compensates for gross head motion. The position of the head when the eye is lost is detected through a search pattern. See Fig. 4.30.

With the EG&G/HEL system, the subject sits in a chair and views a projection screen without even having to know that his eye is being observed with a camera located underneath the screen. This camera leads to a video processing system also attached to a PDP-11 computer. Eye movement and fixation information is extracted and recorded in any of a number of formats including video tape recording and others. See Fig. 4.31.

A variant of the basic single corneal reflection-pupil center vector method was used by Hochberg (1974). He employs two corneal reflection spots to eliminate the effect of distance variation from the optics to the subject or overall optical system magnification. The separation between the two spots becomes the basic length around which all the other measurements are normalized. This therefor eliminates the need for absolute calibration. The pupil center position is t measured with respect to a point equidistant between the two corneal reflection spots.

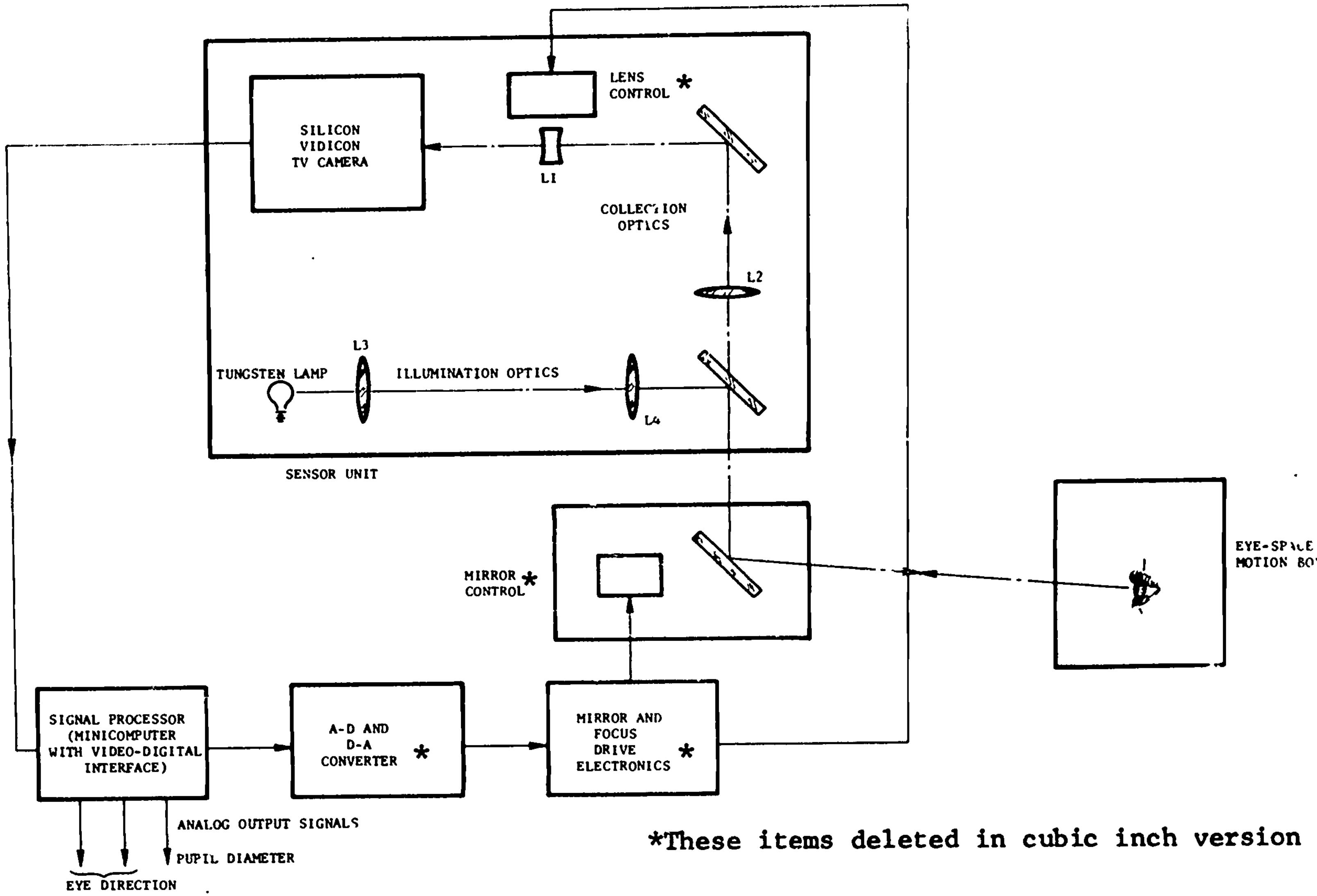


Figure 4.30. Schematic of the Cubic Foot Remote Oculometer.
(Merchant and Morrissette, 1974).

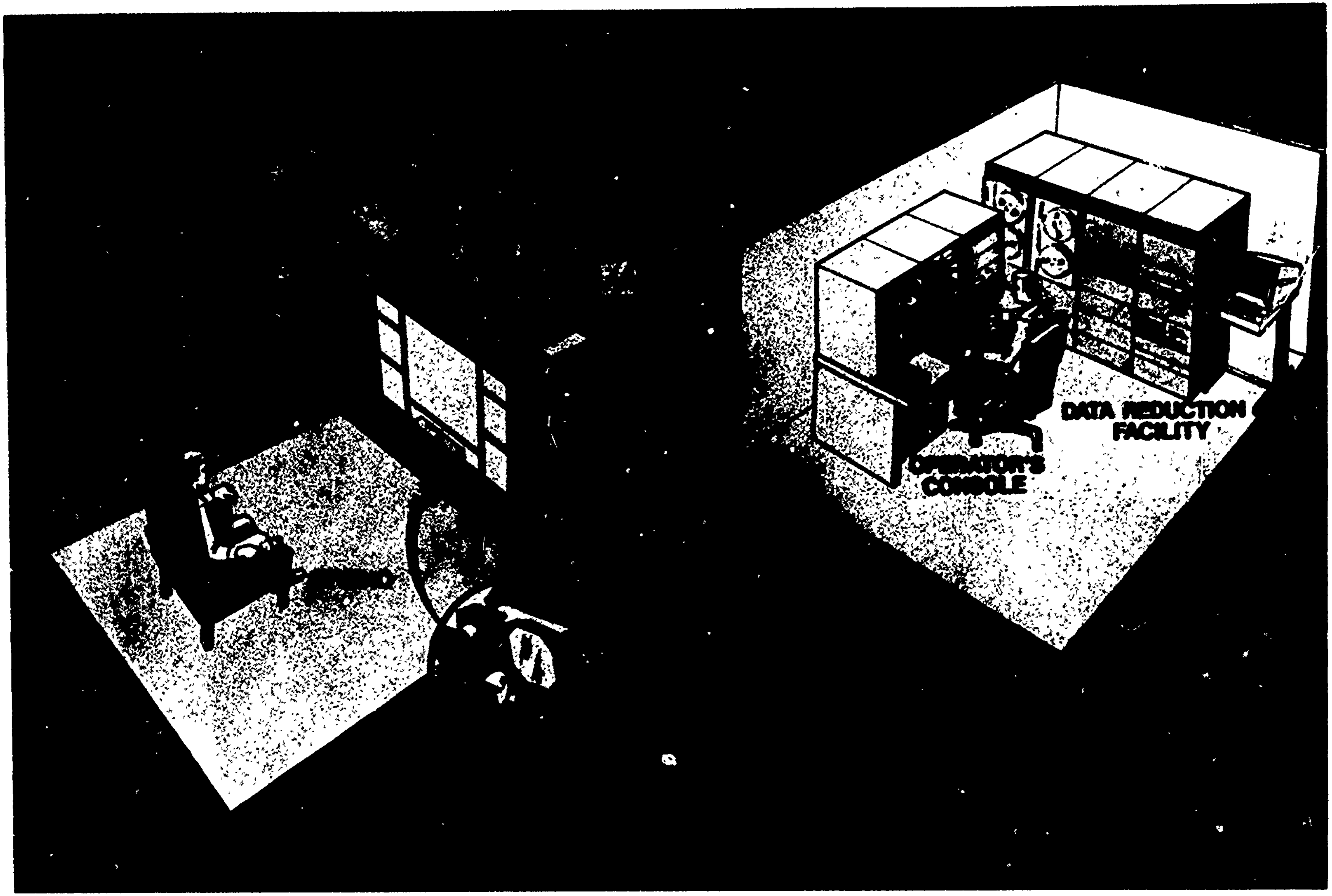


Figure 4.31. EG&G-HEL Oculometer System (Monty, 1974)

Most of these systems use a digital computer. Sophisticated processing is therefore possible and correction and linearization for various limitations of this measurement principle can be overcome. In particular, the corneal reflection method is generally limited by the curvature of the corneal bulge to less $\pm 15^{\circ}$. Beyond that the cornea flattens out and the measurement becomes non-linear, although still monotonic. There may also be imperfections and asymmetries in any individual cornea that makes the measurement non-linear; changes in the tear film also cause a problem. As the pupil constricts and dilates it does not normally maintain a fixed center with respect to the eyeball. All these problems can be eliminated to a large extent by the processing which is incorporated in the computer and circuitry of these systems.

Any system which determines the pupil center for eye movement measurement also can make pupil area or pupil diameter available as an additional output with virtually no additional electronics processing. With continued interest in pupil diameter as a measurement of tension or arousal, this technique offers the ability to monitor the effect on pupil diameter of different portions of the scene being scanned.

At the present time there are two known systems commercially available: 1) The Honeywell Oculometer Mark II which allows a cubic inch of motion and the Mark III which allows a cubic foot of motion; 2) the Whittaker Corporation Eye Movement Monitor is also commercially available and allows about an inch of head motion. The Honeywell unit provides an accuracy of 1° for a maximum range of 60° horizontal and 40° vertical with time constant of 0.1 seconds. The Whittaker unit provides an accuracy of 1° for a range of 40° horizontal and 30° vertical with a sampling rate of 60 per second. Both systems also provide instantaneous pupil diameter.

4.5.3 Evaluation of the Corneal Reflection-Pupil Center Measurement

There is no question that maintenance of a fixed head or attachments to the head are difficult, uncomfortable, unsuitable for many subjects, and may require long set-up time. The methods, therefore, that measure eye point of

gaze relative to space without requiring any head position measurement or stabilization offer considerable advantage. They are comfortable; the data is generally in a form very amenable for processing; and the illumination is usually infrared, and therefore not annoying or disturbing. Many of the units also incorporate a great deal of information and signal processing which allows broadening the limitation of eye movement measurement to a greater range of eye movement and even larger head movements allowances with signal improvements by averaging, linearization and various other corrections.

This advanced and sophisticated instrumentation is more expensive than the various other simpler more direct methods of eye movement measurement. It is also generally bulkier and more involved to learn to use, although easier once learned.

What these methods may lack is speed; the television systems can operate only as fast as 60 samples per second. The basic speed limitation comes from the lag of the TV camera tube. Also, precisions and accuracies are not as good as those that can be obtained with head fixed contact lens, limbus tracking, or corneal reflex methods.

4.6 Measurement of Eye Rotation by the Double Purkinje Image Method

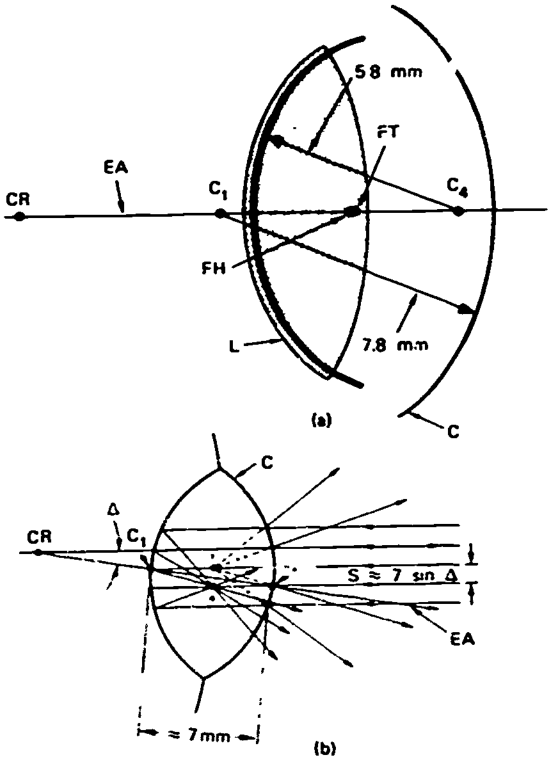
4.6.1 Principle

As light passes through the eye, reflections occur at the various interface surfaces. At the surface of the cornea there is the well known corneal reflection or the first Purkinje image; a second one occurs at the rear surface of the cornea; a third at the front surface of the lens and a fourth at the rear surface of the lens where it interfaces with the vitreous humor. The second Purkinje image is relatively dim; the third Purkinje image is formed in a plane far from the others and these two are not used in this measurement method.

Cornsweet and Crane (1973) used the first and fourth Purkinje reflections as the two features of the eye which they track. Like the relationship between the corneal reflection and the pupil center, these two marks move together under eye translation but differentially under eye rotation.

For purposes of simplicity the two surfaces in question, the front of the cornea and rear of the lens, are assumed to resemble a clam sheil arrangement shown in Figure 4.32 where both surfaces have the same radius of curvature and have a separation equal to their radius of curvature. C_1 is the center of curvature for the cornea and C_4 is the center of curvature of the rear of the lens. If these two surfaces are assumed to be spherical, the effect of collimated incident light is to produce the two images roughly in the center equidistant between the two surfaces. The distance that each image moves as a result of eye rotation is related to the distance from the center of rotation CR to the center of curvature for the surface that forms it. The separation of the two images as a function of eye rotation Δ turns out to be approximately given by $S = 7 \sin \Delta$, where S is in millimeters.

Change in separation between these two images therefore is directly related to the angular rotation of the eye and independent of head translation.



Location of the first and fourth Purkinje images for (a) collimated light on the eye axis and (b) collimated light at angle Δ from optic axis of the eye: EA, eye axis; FT, first Purkinje image; FH, fourth Purkinje image; L, lens; C, cornea. The dark section of arc is the equivalent mirror for the fourth Purkinje reflection.

Figure 4.32. Simple Field Representation of Cornea and Rear Surface of Lens. (Cornsweet and Crane, 1972).

4.6.2 Implementation

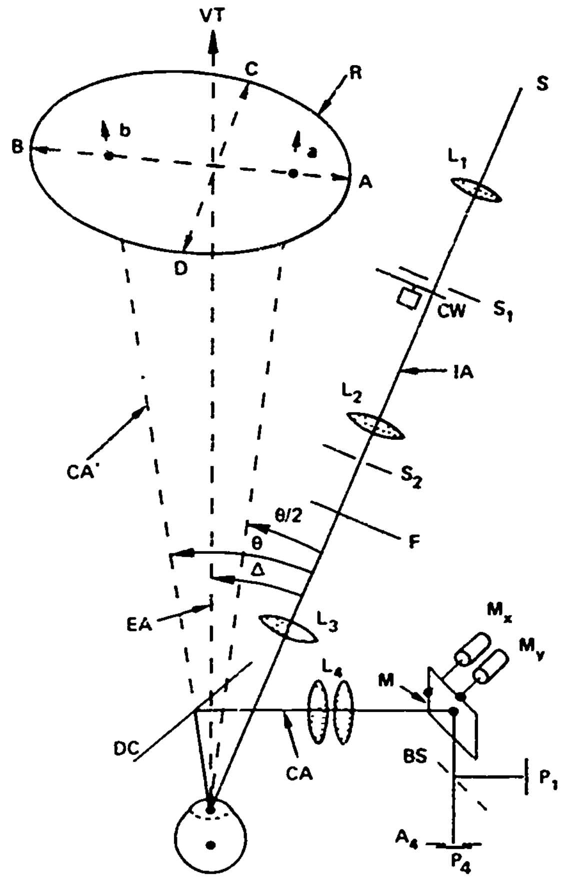
Figure 4.33 shows the optics employed for this kind of measurement. From a light source S, circular aperture S_2 forms two Purkinje images on the eye. Collection optics L_4 view the eye and image the two Purkinje reflections on the two photodetectors P_1 and P_4. These are four quadrant photodetectors which yield a signal proportional to the position of the image off center. They control servomotors to drive each image continuously to center. The final output is the difference in the electrical signals that are generated in the servo-mechanisms required to maintain a centered null condition. As the eye translates, both images move in the same manner and the difference is effectively zero. This is performed in both axes. There is a net shift in the steady-state position of the two Purkinje images because of the optical arrangement and in order to separate them.

This instrument has been developing through a number of stages. The recent units have allowable head motion of ± 0.5 cm in all three axes. Automatic focusing has been included to allow head movements along the optic axis. The field of view allows a coverage of $\pm 15^{\circ}$ vertically and horizontally. Although very precise alignments are necessary to obtain the proper image position, the illumination optics have themselves been controlled to track the motion of the eye and place the illumination on the pupil.

The bandwidth of the system, which is limited by the servo-motors which drive the photodetectors, is quite high, up to 300 Hz. The instrument also boasts an accuracy of 2 minutes of arc in response to 1° of step.

4.6.3 Evaluation of the Double Purkinje Image Eye Tracker

This technique represents a new and promising way of monitoring eye movements. It is the only, head movement independent, eye tracking method which can measure eye position with such accuracies. It has a higher frequency response than the television systems. In these ways it is superior to the pupil center-corneal reflection center method.



Schematic of the eye-tracker optical system: VT, visual target; R, allowed range of eye movements, IA, input axis; CA, collecting axis, CA', extension of collecting axis, S, light source; S_1, artificial pupil imaged at pupil of eye; CW, chopper wheel; S_2, source of Purkinje pattern, imaged at infinity; DC, dichroic mirror; M, front surface mirror; M_x and M_y, motors that drive M in x and y direction, respectively, BS, beam splitter; P_1 and P_4, quadrant photocells; A_4, aperture in front of P_4. Focal lengths of lenses L_2, L_3, and L_4 are 60, 150, and 90 mm.

Figure 4.33. Schematic Layout of the Double Purkinje Image Eye Tracker. (Cornsweet and Crane, 1973).

It is planned to integrate accomodation measurement, using the Stanford Research Institute Optometer (Cornsweet and Crane, 1972), into this system so that the power to the eye is also measured along with eye rotation for what is effectively a 3-dimensional eye position determination.

The eye tracker falls slightly short of other techniques in the field of view ($\pm 15°$) which is pupil diameter dependent. It also requires higher illumination than the other techniques in order to bring the fourth Purkinje image above the noise. The allowable head movement is, still, not very large, but this may also be further increased. It appears also that the optics need to be fairly close to the eye. What the system cannot provide is pupil diameter, but this may also be later incorporated.

From the fact that many of the original limitations in the intial eye tracker design have been overcome and the performance improved, it seems that many of these limitations are only technological rather than inherent restrictions of the approach.

4.7 Measurement of Fixation Point by Determining the Rotation of a Plane Attached to the Eye

4.7.1 General Principles

In this section are grouped the methods which measure some parameter of the eye which varies with eye rotation but is for the most part independent of head translation.

These methods include measurement of the orientation but not translation of some imaginary or real "plane" attached to the front of the eye relative to a fixed observer. One way is to determine the apparent ellipticity of the pupil to an observer. Other ways are to attach just such a plane to the eye, a plane mirror with a contact lens or the plane of a search coil imbedded in a contact lens (Robinson, 1963).

Another method invariant to head motion is the tracking of an image focused on the retina. If an eye is fixating a particular point in space, then that point will always fall on the fovea regardless of head translation or eye rotation. This principle was put into practice by a retinal image tracker developed by Cornsweet (1958). Again the principle here is the measurement of rotation of a plane attached to the retina.

4.7.2 Specific Implementations

4.7.2.1 Ellipticity of the Pupil

When the pupil is viewed head on, it appears circular. If the eye rotates, the pupil will have an apparent ellipticity. The apparent shape of the pupil to a fixed observer will not vary as the head of the subject moves, but only as the subject's eye rotates. If the eccentricity of the pupil is measured therefore, it would indicate the rotation of the eye only. One problem however is that the measure is an even function of eye position and some other course determinants would have to be used to differentiate between up and down and right and left. A second problem is that a rather involved geometrical computation would be required. See Figure 4.34. There have, however, been no successful implementations of this method. (Hall, 1972)

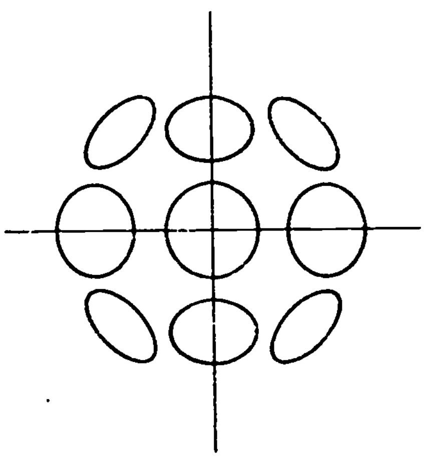


Figure 4.34. Apparent Ellipticity of Pupil as Eye Rotates

4.7.2.2 Contact Lens Method

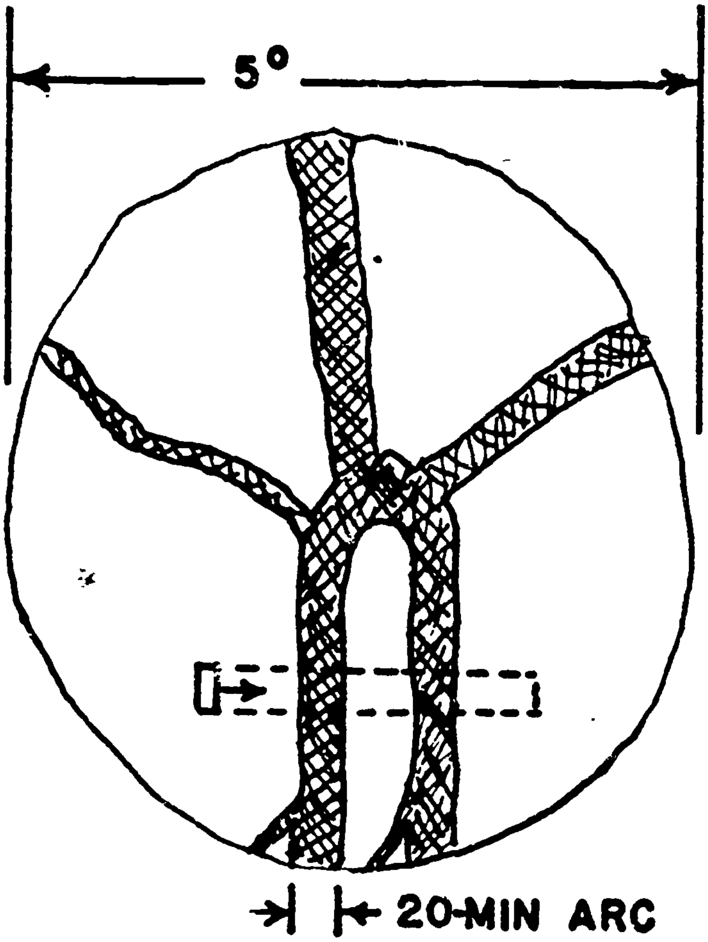
A plane mirror or a search coil attached to the eye provide a geometrical "plane" whose orientation may be determined independent of translation. These two approaches were discussed in detail in Section 4.4.2.

4.7.2.3 Tracking of a Retinal Image

The retina is usually observed under wide field illumination, but if the field were focused to a small spot on the retina and the subject were fixating it, then the image of the illumination spot would clearly remain on the same point on the retina. Clearly also, the retinal image of a second point, near the first and in the same plane would be fixed to the retinal image of the first.

Another way of viewing this concept is to consider a subject looking at a very distant object, say a star; the image would not shift on his retina, if he translates his head, but will obviously move if he rotates his eye. A collimated light source is equivalent to a very distant object.

Cornsweet (1958) had a subject fixate on one point and projected a small rectangle of light on the optic disk as shown in Fig. 4.35. If the relation between the fixation point and the spot is constant, the spot position on the disk shifted only with fixation changes. A pronounced blood vessel was selected on the disk, and the relative shift of the imaged spot was measured by the distance the spot had to be moved to be repositioned on the blood vessel. In other words, whenever fixation changed, the spot went off the blood vessel and was repositioned there. This was actually accomplished by a flying spot scanner which scans this spot, and the instantaneous reflected light was viewed with a photomultiplier. See Fig. 4.36. The time from the beginning of the scan to arrive to the reference and vessel was directly related to shifts in fixation.



Drawing of the optic disk, right eye. The small rectangle is the scanning spot. The dashed lines indicate the locus of its path of movement.

Figure 4.35. Scanning of a Retinal Vessel. (Cornsweet, 1958).

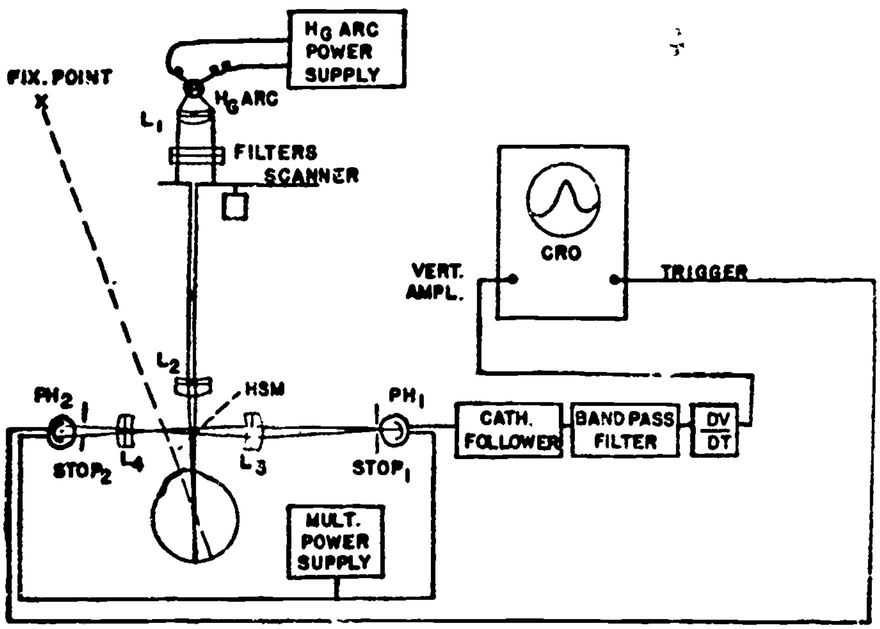


Figure 4.36. Fundus Tracking System. (Cornsweet, 1958).

Resolution of 10 seconds of arc was possible with this method. This was primarily limited by instrument noise. Blood vessel diameter changes, cross-talk from vertical eye motion were also problems. Large eye motion would move the spot off the disk and lose the measurement.

This is a very precise method not requiring a fixed head which seems to be held back only by the practical problems associated with viewing the retina. Technological advances in this areas are certainly possible.

4.8 Head Movement Measurement to Obtain Point of Regard

All of the eye movement monitoring techniques fall broadly into two categories - those that measure the position of the eye relative to the head, and those that measure the orienation of the eye in space. For studies of the eye movement control system, per se, the first category techniques normally suffice. When the concern is with identifying the elements in a visual scene which are being fixated or scanned, however the orientation of the eye in space, or the "point of regard" is required. Any of the first category methods can be adapted for use in the free head fixation pattern application by measurement of head angle and position. See Fig. 4.42. Whether or not head linear position is required in addition to angular orientation depends, of course, on the freedom of head linear displacement permitted, the distance to the material being viewed, and the desired system accuracy. For this consideration, we also review some common techniques for measurement of head position, all of which can be combined with eye position recording to yield the point of regard.

The only eye movement methods which give the angle of gaze relative to a reference point in the visual field are those with a camera mounted to the head, those which track two separate points in different planes on the eye, or those which measure retinal plane rotation. Any of the methods which track a feature on the front of the eye or EOG must be corrected for head position to give the point of regard.

Current and advanced methods of monitoring head angle (head line of sight - LOS), suitable for combination with eye measurement techniques to yield eye point of regard, are given below.

All of the head measurement techniques, with the exception of the eye

tracking video method discussed in conjunction with the corneal reflex-pupil vector systems, require some attachment to the head. The attachments may be as unobtrusive as reflecting surfaces or distinctive optical targets taped to the head, spectacles or bite board, or they may involve a helmet to carry the transducers. Basically five methods have been utilized: optical, ultrasonic, electromagnetic, inertial and mechanical. All but the last can be free of any mechanical connection between the subject's head and his surround.

4.8.1 Optical Head Position Sensors

Optical x-y tracking techniques which have been developed for tracking rockets or small variations in thickness in industrial processes, can be used to locate the x-y coordinates of a small point attached to the head. The basic scanning methods discussed under the corneal reflex implementation are applied to locate the brightest or darkest spot in a scene and servo drive the camera or mirrors to keep it centered. One common variation is the use of a circular scan pattern which uses phase sensitive detection of the video signal to determine the required direction to draw the circle center for alignment over the target as shown in Figure 4.37. These devices can be stabilized to resolve angular motions of a few seconds of arc with appropriate optics. By using three such targets, all translations and rotations of the head could be calculated.

The most common optical head tracking devices employ a helmet of some sort with an array of light sources (or photodetectors) on it, and the complimentary devices fixed to the surround. One such system, built with the idea of measurement of astronaut head angles relative to a large visor or a fixed outer shell is shown in Figure 4.38. It uses three miniature pulsed infra-red LED's on the helmet liner and an array of 8 photodiodes as receivers (Chouet and Young, 1974). The cross-coupling between head angle measurements in various axes is minimized with a small computer and compensation circuit.

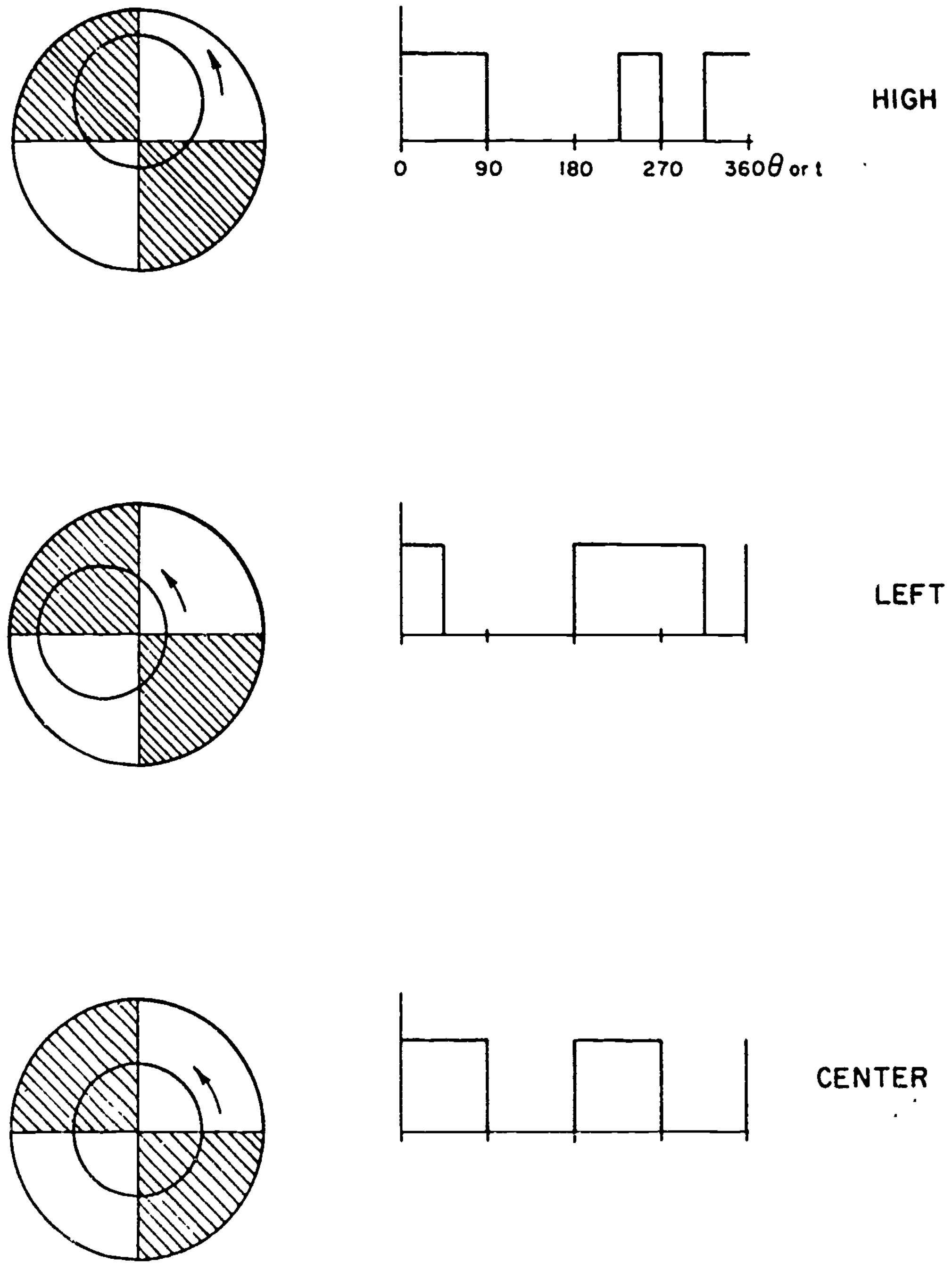
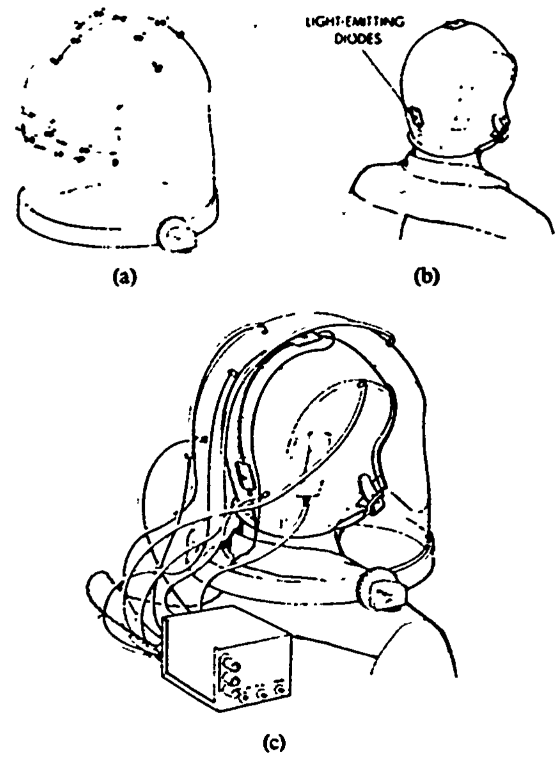


Figure 4.37. Circular Scan X-Y Tracker



(a) Helmet and disposition of eight photodetectors. (b) Helmet liner with two LED. (c) Monitoring equipment.

Figure 4.38. Optical Head Position Sensor (Chouet and Young, 1974).

The need for accurate knowledge of head position for a variety of "Visually Coupled Systems" for hands-off localization and aiming has led to the development of accurate and reliable head line of sight sensing systems. One such system, shown in Figure 4.39, was developed for tracking the pilot's line of sight within the restricted confines of a cockpit (Ferrin, 1973). The Sensor Surveying Unit (SSU), fixed to the laboratory or cockpit, emits two thin fan-shaped beams of IR, which sweep across the photodetectors in the helmet, triggering each one at the moment of intersection. Use of the IR fans and detectors on each side of the helmet increases the range of head motion allowed while still tracking the line of sight. Although this and related systems appear bulky because of the helmet and related display equipment, the actual hardware which must be worn on the head for head tracking is merely two or four miniature photodetectors.

A newer design proposed for the helmet line of sight measurement uses four LED's mounted on a helmet, each one pulsed at a different frequency (Haywood, 1973) (see Figure 4.40). Up to four optical linear position proportional detectors are positioned in the laboratory fixed frame. Each detector measures the x-y coordinates of the image of each source in its field of view, and thereby provides the computer with the information required for the resolution of the line of sight angles of the helmet. The goal for such a system is ±1 degree static accuracy in head pitch and yaw over a range of ±75 degrees about each axis.

4.8.2 Ultrasonic Head Position Sensors

The use of multiple ultrasonic transmitters and detectors on the helmet and in the laboratory permits head position to be sensed by measurement of the distance from each source to each receiver by means of the sonic delay time. Practical implementation of a multiple source

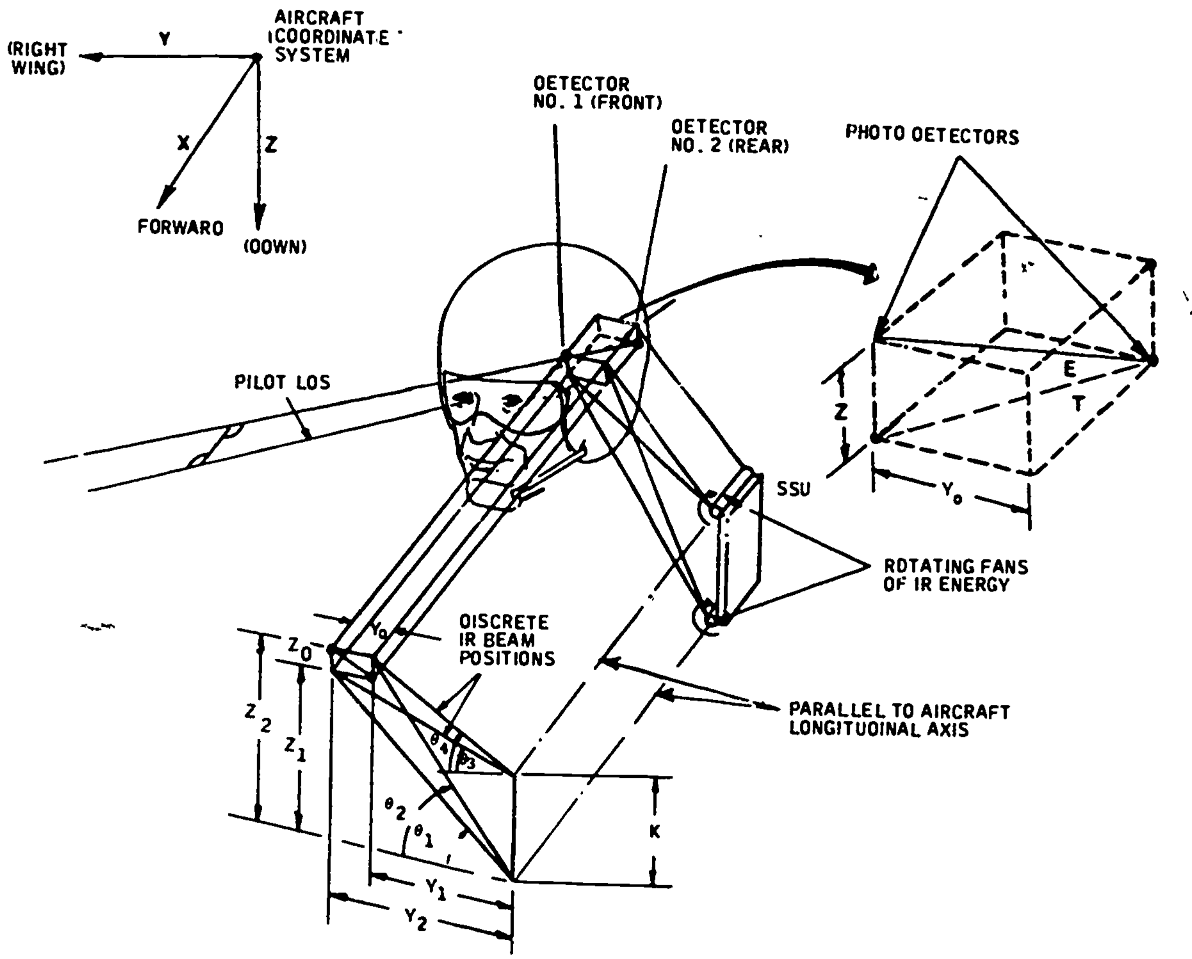


Figure 4.39. Head Line-of-Sight Sensing System (Ferrin, 1973).

system to measure head position and orientation was demonstrated at MIT's Lincoln Laboratory for computer graphics applications. One possible arrangement of ultrasonic transmitters and receivers, shown in Figure 4.41, is especially useful for pitch and lateral rotation head movement sensing (Sawamura, 1973). The weight of the helmet mounted portion can be reduced by mounting the transmitter rather than the receivers on the helmet. Tests of a similar system showed static errors of less than 1 deg rms. with range of up to 360 degrees possible. The ultrasonic sensing systems inherently provide head position as well as orientation information.

4.8.3 Mechanical Head Position Sensors

Head position can be measured by mechanical linkages to the target field. Perhaps the simplest is the attachment of flexible shafts, one for each axis of rotation to be measured, from a helmet to the laboratory bench. Head freedom of motion is restricted somewhat by the cables, depending on their number and length.

The next step in mechanical measurement is a form of goniometer for measuring angles of one body relative to another. These typically consist of rigid or telescoping rods with potentiometers at each linkage to measure head angles. Sperry developed such a rigid linkage system with a magnetic quick disconnect for pilot helmet orientation measurement. A two gimbal system with a vertical and a horizontal potentiometer was combined with a limbus reflection eye movement monitor to yield a practical eye point-of-regard system. One end of the mechanical linkage is attached to a point in the target field, and the other is held between the subjects molar teeth, with a "pipestem" bite board (Klein and Jex, 1970). The device permits head movements of up to 20 cm and eye point of regard measurements of better than one degree accuracy over a range of 20 degrees vertical and 40 degrees horizontal. See Figure 4.42. The same technique can be applied

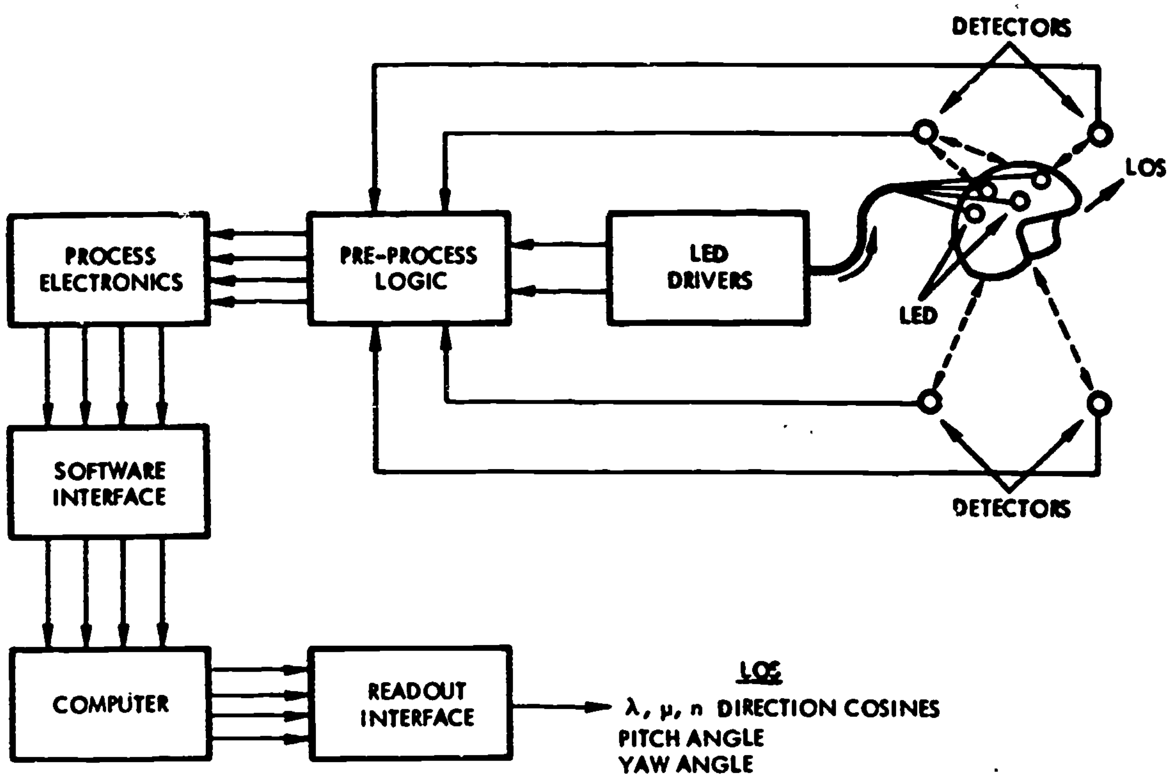


Figure 4.40. LED Line-of-Sight Head Position Measurement System. (Haywood, 1973).

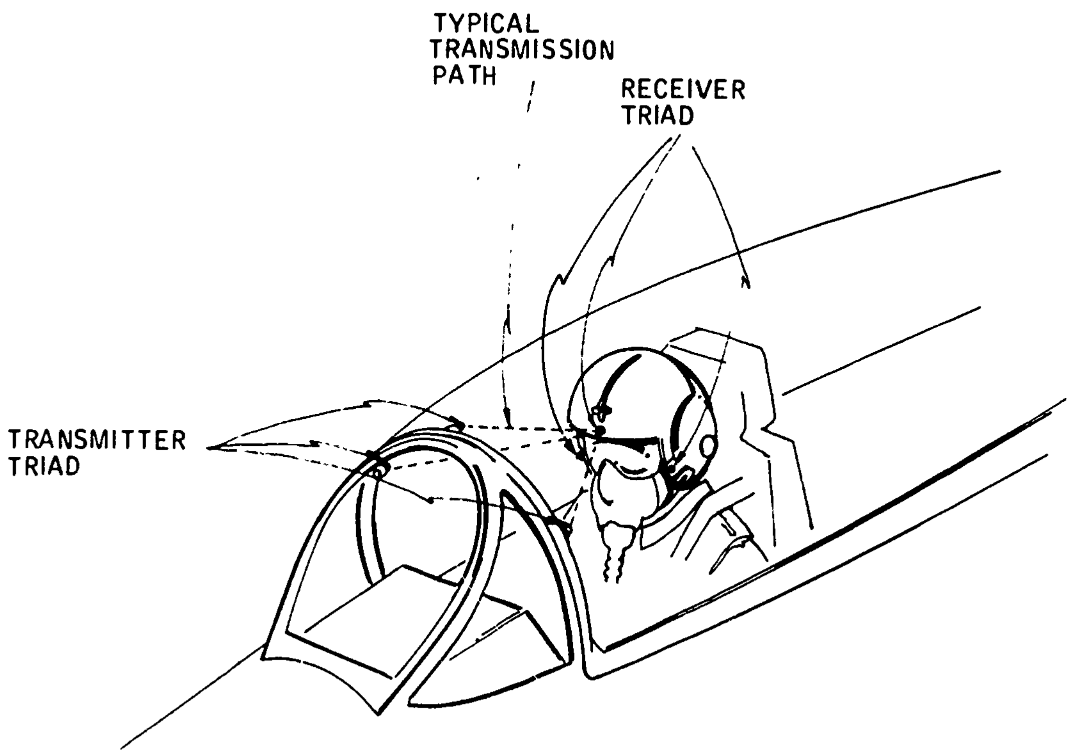


Figure 4.41. Ultrasonic Head Position Measurement System. (Sawamura, 1973).

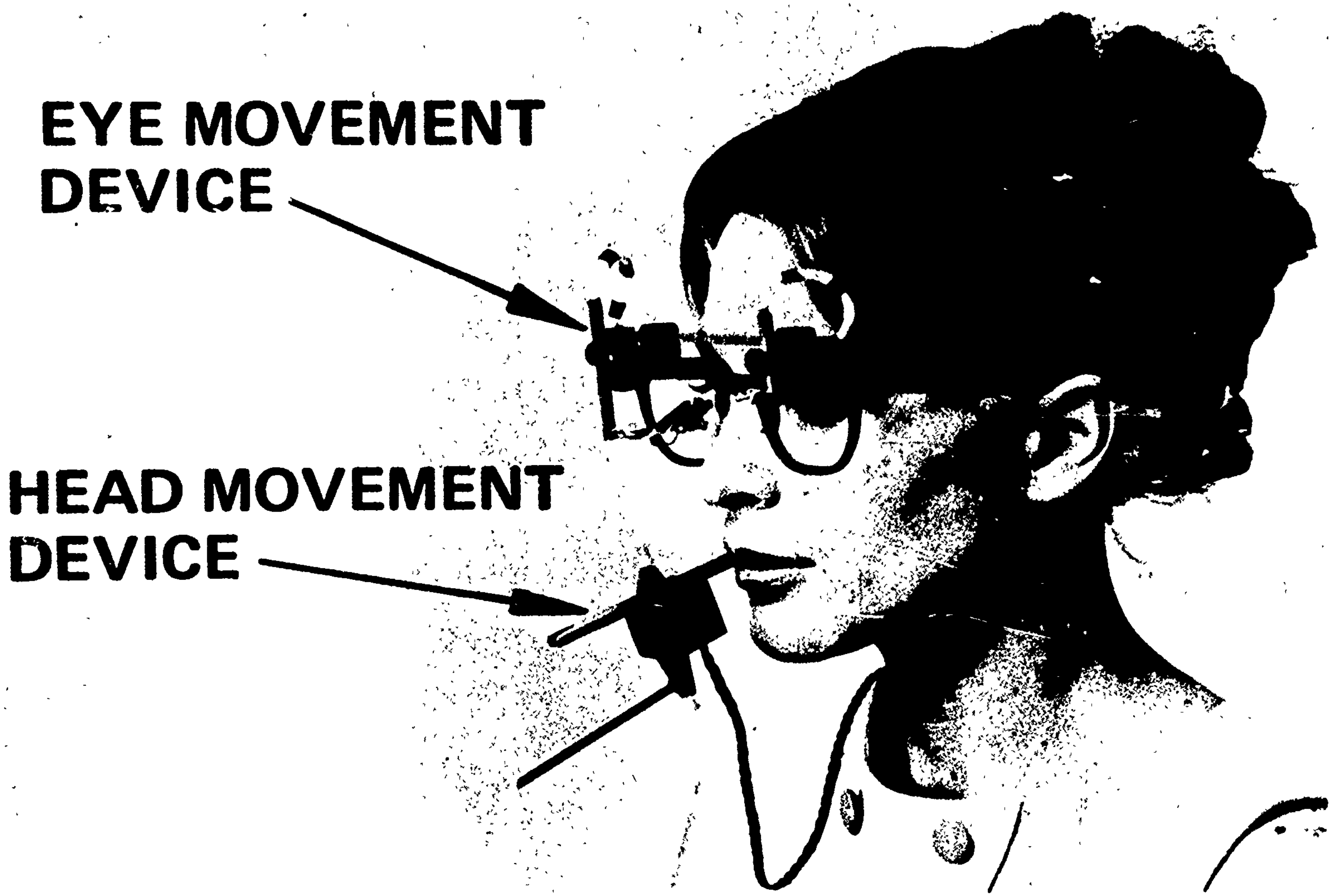


Figure 4.42. "Pipestem" Bite Board Device for Head Position Measurement Incorporated with an Eye Movement Device. (Courtesy Systems Technology, Inc.).

to measurement of the head position and orientation in all six degrees of freedom by measuring all linkage angles and lengths. The six degree of freedom system allows accurate head position measurement within a volume approximately two feet high and six feet in diameter, allowing full freedom in yaw, and pitch of 30 degrees upward and 80 degrees downward.

An additional high accuracy mechanical head position sensor was developed by Vickers (1972) using a telescoping tube with one end attached to the ceiling and the other to the subject's head set via a universal joint. The weight of the apparatus was supported by constant tension springs. Six rotary pulse generators at the head set measured the six degrees of freedom changes in position with resolution of hundredths of an inch in translation and 0.3 arc minutes in rotation within a volume approximately 2 feet high and 5 feet in diameter.

4.8.4 Inertial Head Position Sensors

Inertial measurements of head motion can be made with miniature gyroscopes and accelerometers mounted on the helmets. The size and expense of systems to measure position accurately enough for eye fixation work is currently not justified. However, for gross measures of subject angular velocity or acceleration, as for studies of vestibular nystagmus, such systems are practical (Howland, 1961). When linear accelerometers are used, care must be taken to separate the effects of rotations of the sensitive axis into the gravity vector from pure linear accelerations, including the tangential and centripetal accelerations associated with rotation. Simultaneous telemetry of eye movements (EOG) and head linear acceleration during ballet rotation is useful in a qualitative assessment of head and eye movements (Tokita et al, 1973).

4.8.5 Electromagnetic Head Position Sensors

Steinman (1974) described the use of Robinson's search coil (1963) placed on a subject's eyeglass frames to detect the angular position of his head. The subject was seated with sensing magnets around him and the measurement was made of the relative orientation of the search coil with respect to the magnetic field produced by the surrounding system.

5. TRADE OFFS AND GENERAL CONSIDERATIONS IN INSTRUMENTATION SELECTION FOR READING RESEARCH

5.1 Tradeoffs

Fortunately, for a particular eye movement instrumentation requirement, such as reading research, not all of the highest performance criteria of the various measurement aspects are needed to produce useful results. Clearly some parameters are more important than others and the best possible system that meets the minimum requirements can be chosen and employed.

As an example, a researcher may not be interested in or need to detect fine eye movements; he may not need to look at the high frequency details of a saccade; or his range requirements may be small. He may therefore be satisfied with a simpler less powerful instrument.

One of the first and most important trade-offs is that of subject comfort and set-up time as opposed to accuracy and precision. One is invariably at the expense of the other. Very high maximum accuracy of about 0.01° may be obtained with tight-fitting contact lenses, but set-up and discomfort shortcomings are obvious. Another trade-off is that of range and accuracy. A very high range of greater than $\pm 50^{\circ}$ can be obtained with electro-oculography. That, however, is at the expense of poor DC accuracy, a high percentage of lost data, considerable set-up time and artifact problems. Another trade-off is that between speed and noise. When video signal data or other measuring systems that would inherently generate noise are used, averaging and filtering may be used to reduce the noise, but the price paid here is lowered frequency response.

One very important trade-off against most of the parameters is cost. One can almost always pay more and get higher performance. This is apparent in the newer devices and systems that employ sophisticated optics and electronics to yield eye position measurement.

In reading research, it may be eye movements in themselves that are of interest, the saccades, regressions, fixations, blinks, etc. It may often

not be necessary to relate this information to actual points in the scene. In this case a method like EOG or a spectacle mounted limbus tracker may be the most suitable since a virtually free head is tolerated and satisfactory data is obtained. If point of fixation is needed, however, some head fixing or measuring method is needed or a point of regard system must be especially built or purchased at a higher cost. Performance may also be reduced.

If testing of children is considered, then a system must be chosen which requires minimal subject training or cooperation. This may preclude the use of contact lens methods or even EOG under some experimental conditions. In these cases, an instrument which can be set up quickly with minimum calibration would be needed.

Considerable thought should also be given to handling the data coming out of the eye movement measurement instrumentation. Again, there is a trade-off. The simpler and the cheaper the form of the output, the harder it is to process. A photograph or a video tape is a simple output, but is hard to handle. An analog signal output is the next step up. It is easier to handle and to view but may still pose some difficulties in large data analysis. A digital recordable output that goes on digital tape or into a computer is most amenable to sophisticated analysis but is the most costly and difficult to interface. Also time and expense is required for the programming to extract the desired information.

Future development should be directed at breaking down the existing limitations of the best existing systems. There can be two philosophies of the most suitable kind of instrumentation for reading research; first, the concept of a highly sophisticated eye movement research test center. This would be a facility to which researchers would bring their experiments and their subjects, as opposed to maintaining their own extensive equipment for eye movement research. In this manner an expensive and sophisticated eye movement measurement instrument can be employed by a large number of groups. The disadvantage, of course, is that

the experimenter must travel to the instrument, but he would not have to pay for its exclusive use.

Such a facility might be comparable to the one at the U.S. Army Human Engineering Laboratory (Hall,1973) which could be employed for reading experiments. Some of the limitations of this particular existing system can be overcome to allow higher accuracies or greater head motion or other desired improvements.

The second approach is to have a unit that is suitable for the laboratory. This implies a somewhat less expensive system, and consequently one that may not be as powerful. There are probably no units presently existing that would be ideal for all applications, but a number of institutions and commercial firms are in the field, and technological advances have been coming rather rapidly.

Unless and until the specifications for a particular requirement such as reading experiments are very carefully determined and set down, it is difficult if not impossible to establish a meaningful cost effectiveness of the various potential instruments and techniques. Clearly, if a particular device just does not satisfy the requirements desired, then it is virtually of no value and one will just have to pay for the next higher performing unit which will. One meets the phenomenon of diminishing returns where, for example, an expensive computer must be used to improve a parameter like accuracy ,linearity or range by just a few percent.

5.2 Simultaneous Psycho-physiological Measurement

In addition to eye movement and position, there are two human eye functions from which psychological inferences can be drawn and there is a great deal of literature available in the field. The first is blinking. Almost all of the eye movement measurement methods will have blinks as an output artifact. It can clearly be picked out in a photograph, in an EOG record or in all the systems that track the limbus, the pupil or the corneal reflection. In methods providing

an electronic output it can clearly be seen as a pulse with a characteristic blink duration. The second parameter is pupil diameter. There is considerable controversy in the scientific community as to whether pupil diameter is an indicator of positive and negative emotion with dilation indicating the former and constriction the latter. But there is general agreement, however, that pupil dilation is an indicator of emotional activity, whatever the sign. It is therefore very convenient to record pupil diameter, especially if it is part of the eye movement measurement output, and to correlate that with what part of the scene the subject is viewing. Some of the existing commercial eye movement monitor systems give pupil diameter as an output. Koff et al (1971) compiled a comprehensive bibliography on pupillary response.

For other psychophysiological measures, some consideration must be given to their compatibility with eye movement measurements. For example, if the required test will encumber the subject and keep him stationary, there is no value in obtaining an expensive eye movement system that would allow free subject head motion. If electro-encephalography is being performed and electrodes are attached to the subject's head, then EOG may be a reasonable measurement method since the electrodes are similar and the procedure is being made anyway. This, of course, assuming that it fulfills the other experiment requirements.

It is also important to be able to simultaneously record the eye position measurement output along with the measures being taken in a compatible format where the time element is either recorded or may be deduced. Some marker or indication of stimuli presentation should also be recorded. In this way only, can the various parameters being recorded be correlated to the stimuli. Unless the effects of the inputs are strikingly apparent, statistics might be needed to relate cause and effect where the latencies are not known. This is one reason why digitized outputs amenable to computer handling are desirable.

6. COMPARATIVE TABLES OF EYE MOVEMENT MEASURING TECHNIQUES

TABLE 1. COMPARISON OF EYE-MOVEMENT

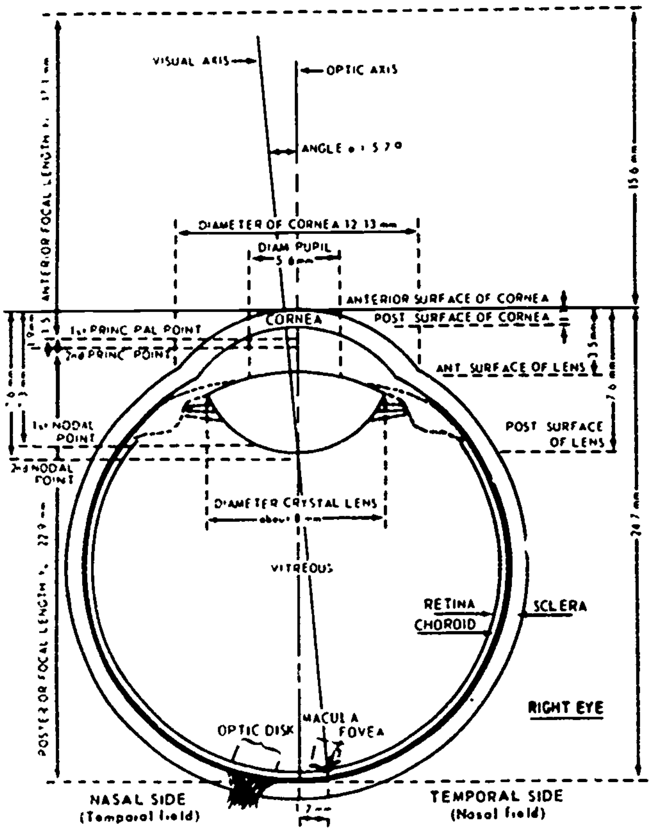
Method	Measurement range: Vertical	Measurement range: Horizontal	Accuracy: Vertical	Accuracy: Horizontal	Speed or frequency response	Interference with normal vision	Glasses acceptable	Contact lens acceptable	Subject variation problems, eye color, etc.	Subject cooperation required	Subject training required	Usable with young children
1. Corneal reflex (Mackworth Camera) Polymetric Lab VII64	±9°	±9°	.5°	5°	Photographic rate, 12–64 frames/sec Television · 60 field/sec	Medium	?	Possible source of error	None	High	Low	?
Polymetric Mobile VO165	±10°	±10°	1°	1°	Same as above	High weight on head, optics near eye	No	Possible source of error	None	High	Low	No
NAC-REES	±10°-20°	±10°-20°	2°	2°	Same as above	High · weight on head	No	Possible source of error	None	High	Low	No
2. Contact lens with						High		No	Eye must accept contact lens	High	High	No
lamp or radiant spot	both ±10°–±30°		Precision 3″	3″	High		No					
coil	larger than others		15″	15″	High		Yes					
mirror	±10°	±10°	2″	2″	High		No					
3. EOG	±50°	±50°–±80°	2°	1.5°	dc or .01–15 Hz limited by filtering	None	Yes	Yes	Medium: placement of electrodes and calibration is variable	Medium	Low	Yes
4. Limbus Boundary Biometrics Eye Trac	±10°	±10°	4°	2°	2 msec. 30 msec with recorder	Medium	Yes	Yes	Iris coloration a factor	High	Low	Yes
Biometrics Model 200	+10° −20°	±20°	2°	1°	4 msec. 26 msec with filtering	Medium	No	Yes	Iris coloration a factor	High	Low	Yes
5. Wide-Angle Mackworth Camera Polymetric VII66	40°	40°	2.5°	2.5°	Same as Method 1	Medium · subject looks through apertures; special lighted stimuli are required	?	Possible source of error	None	High	Low	Yes
6. Pupil-center–corneal-reflection distance Honeywell Oculometer	+30°–10°	±30°	1°	1°	.1 sec time constant	Low	Yes	Possible source of error	Low	Low	Low	Yes
Whittaker eye view monitor	±15°	±22°	1°	1°	30–60 samples/sec	Low	Yes	Same as above	Low	Low	Low	Yes
U.S. Army Human Engineering Lab	30°	40°	2°	2°	60 samples/sec filtered	Low	No	Same as above	Low	Low	Low	Yes
7. Double Purkinje image eye tracker	±15°	±15°	Precision few minutes		300 Hz	Low	Possible source of error		Low	Low	Low	Yes

Calibration and setup time	Head attachments required	Head stabilization requirement (to make measurement, not to obtain fixation point)	Subject discomfort	Subject awareness	Pupil diameter output also	Form of output	Status	Cost of operation	Remarks	Source of further information
Low	Chin rest or biteboard	High head restraint or biteboard	Medium	High	No	Photographic or videotape; low-resolution digital output	Commercially available	High for film	—	Polymetric Co. 1415 Park Avenue Hoboken, NJ 0703[illegible]
High: biteboard	Biteboard	None	High	High	No	Same as above	—	High for film	Higher resolution digital output is possible with other instruments	--
Medium: fit headband, set light source	Head-mounted optics	None	Medium	High	No	Same as above	—	High for film	--	Instrumentation Marketing Corp. 820 South Mariposa Burbank, CA 9150[illegible] REES Inst. Ltd. Westminster House Old Woking, Surrey, United Kingdom
High: lens must be fitted	Contact lens		High	High	No	Photographic or electrical	Some commercial devices available	Lens grinding may be costly	Negative pressure application may be hazardous	--
		High								
		Low								
		Low								
High: requires electrode stabilization and light adaptation	Yes, 2-6 electrodes	Low	Low	High	No	Electrical record	Commercially available	Low	—	LT Instruments 4004 Osage Houston, TX 7703[illegible] Grass Inst. Quincy, MA 02169 ICS 129 Laura Drive Addison, IL 60101
Low	Head bracket and chin rest	High	Low	High	No	Analog and digital	Commercially available	Low	Vertical position of lower eyelid is used to approximate vertical eye position	Narco Bio-Systems Inc. Biometrics Division 7651 Airport Blvd. Houston, TX 77017
Low	Spectacles	None	Low	High	No	Analog and digital	Commercially available	Low		Narco (also see ICS)
Low	Viewing through aperture	Medium, head must be kept still	Low	High	No	Photographic or videotape; low-resolution digitizer available	Commercially available	High for film	Point of regard output without head motion artifact	Polymetric Co. (see above)
Low, higher for maximum linearization	None	Mark II, head free, 1 in³ Mark III head free, 1 ft.³	Low	Low	Yes	Digital, analog, and fixation pointer on TV image of scene	Commercially available	Low	Computer-based system Mark III tracks head motion and has auto focus	Honeywell Radiation 2 Forbes Road Lexington, MA 02172
Low	None	Head free up to 1 in³	Low	Medium	Yes	Same as above	Commercially available	Low		Whittaker/Space Sciences 335 Bear Hill Road Waltham, MA 02154
Low	None	1 ft.³	Low	Low	Yes	Digital, analog, videotape, and graphic	Research laboratory	NA		U.S. Army/HEL Aberdeen Proving Ground, MD
Low	None (chin rest or biteboard?)	None, head free 1 cm³	Low	Medium	No	Analog output	Small production	Low	Has auto focus; field and operation are dependent on pupil size	Stanford Research Institute Menlo Park, CA 94025

APPENDIX A

SCHEMATIC OF THE EYEBALL

a.



b.

Constant	Eye Area or Measurement	
Refractive index	Cornea	1 37
	Aqueous humor	1.33
	Lens capsule	1.38*
	Outer cortex, lens	
	Anterior cortex, lens	
	Posterior cortex, lens	
	Center, lens	1 41
	Calculated total index	1.41
	Vitreous body	1 33
Radius of curvature, mm	Cornea	7.7
	Anterior surface, lens	9.2-12 2
	Posterior surface, lens	5 4-7 1
Distance from cornea, mm	Post surface, cornea	1.2
	Ant surface, lens	3.5
	Post. surface, lens	7 6
	Retina	24 8
Focal distance, mm	Anterior focal length	17.1 [14 2]**
	Posterior focal length	22 8 [18 9]
Position of cardinal points measured from corneal surface, mm	1. Focus	-15 7 [-12.4]
	2. Focus	24 4 [21 0]
	1. Principal point	1 5 [1 8]
	2 Principal point	1 9 [2 1]
	1 Nodal point	7 3 [6 5]
	2. Nodal point	7 6 [6 8]
Diameter, mm	Optic disk	2-5
	Macula	1-3
	Fovea	1 5
Depth, mm	Anterior chamber	2 7-4 2

*Cortex of lens and its capsule

**Values in brackets refer to state of maximum accommodation

The diagram and table give dimensions and optical constants of the human eye. Values in brackets shown in the table refer to state of maximum accommodation. The drawing is a cross section of the right eye from above

The horizontal and vertical diameters of the eyeball are 24.0 and 23.5 mm, respectively. The optic disk, or blind spot, is about 15 degrees to the nasal side of the center of the retina and about 1.5 degrees below the horizontal meridian.

Figure A-1. Schematic and Optical Constants of the Eyeball. (Roth, 1968, after White, 1964 and Spector 1956).

REFERENCES

A. Optical Co. "Rhythm Reading - The Ophthalmograph" (1937), Sci. Instruments Div., Southbridge, Mass.

Barlow, H.B."Eye movements during fixation." J. Physiol.,(1952),116-290.

Bles, W. and T.S. Kapteyn, "Separate recording of the movement of the human eyes during parallel swing tests",Acta Otolaryng, (1973),75,6-9.

Bond, H.W. and P. Ho,"Solid miniature silver-silver chloride electrodes for chronic implantation,"Electroenceph. clin. Neurophysiol.,(1970) 28, 206-208.

Boyce, P. R. and D.C. West, "The frequency responses of contact lens stalk assemblies", Vision Research, (1968), 8,475-480.

Buswell, G., How People Look at Pictures, University of Chicago Press, Chicago, 1935.

Byford, G.H., "A Sensitive Contact Lens Photoelectric Eye Movement Recorder", IRE Trans. Bio-Med. Electron., (1962) BME-9,236-243.

Carmichael, L. and W. F. Dearborn, Reading and Visual Fatigue, Houghton Mifflin Company, Boston, 1947.

Chouet, B.A. and L.R. Young, "Tracking with Head Position Using an Electro-optical Monitor", IEEE Trans. on Systems Man and Cybernetics,(1974) SMC-4,192.

Cook, G.,"Control System Study of the Saccadic Eye Movement System", Sc.D. thesis, Massachusetts Institute of Technology, 1965.

Cornsweet, T.N., "New Technique for the Measurement of Small Eye Movements", J. Opt. Soc. Am., (1958) 48, 808.

Cornsweet,T.N. and H.D. Crane, "Experimental Study of Visual Accomodation", NASA CR-2007, March 1972.

Cornsweet, T.N. and H. D. Crane, "Accurate Two-Dimensional Eye Tracker Using First and Fourth Purkinje Images", J. Opt. Soc. Am., (1973), 63:8, 921.

Davis, P.W., J.S. Lutz, A. Warner, and A. A. Fannini, "Design and Construction of a Portable Oculometer for Use in Transportation Oriented Human Factors Studies", Department of Transportation Technical Report, DOT-TSC-OST-71-13, 1971.

Delabarre, E.B., "A Method of Recording Eye Movements", Am. J. Psychol., (1898) 9, 572.

Ditchburn, R.W., and B. L. Ginsborg, "Involuntary Eye Movements During Fixation", J. Physiol., (1953) 119, 1.

Fender, D.H., "Contact Lens Stability", Biomed. Sci. Instr., (1964) 2,43-52.

Ferrin, F., "F-4 Visual Target Acquisition System", Symposium on Visually Coupled Systems: Development and Application, Medical Division AMRL, Technical Report AMD-TR-73-1, 1973.

Findlay, J.M. "A Simple Apparatus for Recording Microsaccades During Visual Fixation", Quarterly Journal of Experimental Psychology (1974) 26, 167-170.

Forgacs, P, K. Jarfas, L. Kun, "Recording of Forgacs Photonystagmographic Method", J. Laryngol.-Otol., (1973) 87, 347-364.

Gabersek, V., "Donnees electronystagmographiques des nystagmus spontanes en derivations binocularies et monoculaires", Revue de Laryngologie (1969).

Geddes, L.A., J. D. McCrady and H.E. Hoff, "The Impedance Nystagmogram--a Record of the Level of Anesthesia in the Horse," Southwestern Vet., (1965) 19.

Gonshoor, A., and R. Malcolm, "Effect of Changes in Illumination Level on Electro-oculography", Aerospace Med., (1971) 41, 138-140.

Haith, M., "Infrared Television Recording and Measurement of Ocular Behavior in the Human Infant," Amer. Psychologist,(1969) 24, 279-283.

Hall, R.J. and B. L. Cusack, "The Measurement of Eye Behavior: Critical and Selected Reviews of Voluntary Eye Movement and Blinking", U.S. Army Human Engineering Laboratory, Technical Memorandum 18-72, 1972.

Hall, R.J., M. A. Rosenberg and R. A. Monty,"An Experimental Investigation of the Visual Behavior of Young Heroin Addicts and Matched Controls", U.S. Army Human Engineering Laboratory, Technical Memorandum 25-73, 1973.

Haywood, W.J. Jr.,"New Precision Electro-Optical Technique for Measuring Pilot Line of Sight in Aircraft Coordinates",Symposium on Visually Coupled Systems: Development and Application, Medical Division AMRL, Technical Report AMD-TR-73-1,1973.

Hochberg, J. Personal Communication to D. Sheena.

Howland, H. R., An Angular Head Position Indicator, S.B. Thesis, Elec. Eng., Massachusetts Institute of Technology, Cambridge, Mass. 1962.

Ishikawa, S., A. Yamakazi, K. Inabi and M. Naito, "A New Instrument For Registering Eye Movement (X-Y Tracker)", Acta Soc. Ophthalmol. Jap. (1971) 75, 1110-1117.

Jeannerod, M., P. Gerin, and J. Rougier, Rev. Oto-Neuro-Ophthalmol.,(1966) 38,51-53.

Jones, R., "Two Dimensional Eye Movement Recording Using a Photoelectric Matrix Method", Vision Research (1973) 13, 425.

Klein, R.H. and H. R. Jex, "An Eye Point of Regard System for Use in Scanning and Display Research", Presented at the 15th Annual Technical Symposium of the Society of Photo-Optical Instrumentation Engineers, Anaheim, California, September 1970.

Kaufman, L. and W. Richards, "Spontaneous Fixation Tendencies for Visual Forms", Percept. and Psychophys., (1969), 5,85-88.

Koff, R.H., D. Elman, and A. Wong,"Bibliography and Classification of the Literature of Pupillary Response", HEW Office of Education Contract No. OEC-6-10-079, 1971.

Kris, C.,"Vision: Electro-Oculography" in Medical Physics, O. Glasser, ed., The Yearbook Publishers, Chicago, 1960.

Mackensen, G., "Die Geschwindigkeit horizontaler Blickbewegungen Untersuchungen mit Hilfe der Electrooculographic, Arch. Ophthalmol., (1958) 160,47-64.

Mackworth, N.F. and H. H. Mackworth,"Eye Fixations Recorded on Changing Visual Scenes by the Television Eye-marker", J. Opt. Soc. Am., (1958) 48,439.

Marg, E., "Development of Electro-oculography--Standing Potential of the Eye in Registration of Eye Movement", AMA Arch. Ophthalmol., (1951)45,169.

Matin, L. and D. G. Pearce, "Three Dimensional Recording of Rotational Eye Movements by a New Contact Lens Technique", Biomed. Sci. Instr., (1964) 2, 79-95.

Merchant, J., "Laboratory Oculometer", NASA CR-1422, October 1969.

Merchant, J. and R. Morrissette, "Remote Measurement of Eye Direction Allowing Subject Motion Over One Cubic Foot of Space," IEEE Transactions on Biomedical Engineering, (1974) BME-21, 309-317.

Mitrani, L., N. Yakimoff, and S. L. Mateeff, "Combined Photoelectric Method for Detecting Eye Movements", Vision Research (1972) 12, 2145.

Monty, R.A., "An Advanced Eye Movement Measuring and Recording System Featuring Unobtrusive Monitoring and Automatic Data Processing" American Psychologist, 1975, 30, 331-335.

Mowrer, O. H., R. C. Ruch, and N. E. Miller, "The Corneo-retinal Potential Difference as the Basis of the Galvanometric Method of Recording Eye Movements", Am. J. Physiol.,(1936) 114, 423.

Nachmias, J., "Two-dimensional Motion of the Retinal Image during Monocular Fixation", J. Opt. Soc. Am., (1959) 49,901-908.

Nayrac, P., G. Milbled, Ph.-J. Parquet, M. Leclercq, and G. Dhedin, "Un nouveau procede d'enregistrement des mouvements oculaires. Application aux tests de tracking." Lilie Medical, (1969) 14, 685-687.

Park. R.S., and G. E. Park, "The Center of Ocular Rotation in the Horizontal Plane", Am. J. Physiol., (1933) 104,545.

Petruk, M.W. and S. Hunka, "Oculometer Laboratory Systems", The Canada Council Research Project S71-0890, Final Report, February 1974.

Rashbass, C.,"New Method for Recording Eye Movements", J. Opt. Soc. Am. (1960) 50,642.

Rashbass, C. and G. Westheimer, "Disjunctive Eye Movements", J. Physiol, (1961) 159,361.

Ratliff, F. and L. A. Riggs, "Involuntary Motions of the Eye During Monocular Fixation", J. Exptl. Psychol.,(1950) 40, 687-701.

Richards, W. and L. Kaufman,"'Center-of-gravity' tendencies for fixations and flow patterns", Perception and Psychophysics, (1969)5:2,81-84.

Richter, H.R., "Principes de la Photo-electronystagmographie," Rev. Neurol., (1956) 94,138.

Riggs, L.A. R. Ratliff, J.C. Cornsweet, and T. N. Cornsweet, "The Disappearance of Steadily Fixated Test-objects," J. Opt. Soc. Am.,(1953) 43,495.

Robinson, D.A. "A Method of Measuring Eye Movement Using a Scleral Search Coil in a Magnetic Field", IEEE Trans. Bio-Med. Electron., (1963) BME-10, 137-145.

Robinson, D.A., "The Mechanics of Human Saccadic Eye Movements", J. Physiol., (1964) 174,245-264.

Robinson, D.A., "The Mechanics of Human Smooth Pursuit Eye Movement, J. Physiol, (1965), 180, 569-591.

Roth, E.M., "Compendium of Human Responses to the Aerospace Environment", NASA CR-1205(I), 1,2, November 1968.

Salapatek, P. and W. Kessen, "Visual Scanning of Triangles by the Human Newborn", Journal of Experimental Child Psychology (1966) 3,155-167.

Sawamura, R.T., "The Ultrasonic Advanced Helmet-Mounted Sight", Symposium on Visually Coupled Systems: Development and Application, Medical Division AMRL, Technical Report AMD-TR-73-1, 1973.

Schott, E. Uber die Registrierung des Nystagmus und anderer Augenbewegungen vermittels des Seitengalvenometers. Deutsches Archiv fur Klinische Medizin, 1922, 140, 79-90.

Shackel, B., "Review of the Past and Present in Oculography", Medical Electronics, Proceedings of the Second International Conference, Hiffe and Sons, London, 1960, 57.

Sheena, D., "A System for Instantaneous Wide Angle Eye Position Measurement", Ph.D. Thesis, Massachusetts Institute of Technology, June 1969.

Sheena. D., "Two Digital Techniques for Eye Position Measurement", presented at the Eighth Annual meeting of the Assoc. for the Advancement of Medical Instrumentation, Washington, D.C. 21-24 March 1973. Medical Inst., (1973) 7:1, 78.

Sheena, D. "Pattern Recognition Techniques for Extraction of Features of the Eye from a Conventional Television Scan", Eye Movements and Psychological Processes, Monty, R.A., and Senders, J.W. eds., Washington, National Academy of Sciences, 1976, Lawrence Erlbaum Associates, Hillsdale, New Jersey.

Smith, W.M. and P. J. Warter, "Eye Movement and Stimulus Movement; New Photoelectric Electromechanical System for Recording and Measuring Tracking Motions of the Eye", J. Opt. Soc. Am., (1960) 50,245.

Spector, W. S., (ed.), "Handbook of Biological Data, WADC-TR-56-273, (Oct. 1956), Wright Air Dev. Center, Wright-Patterson AFB, Ohio, (AD-110501).

Stark, L. and A. Sandberg," A Simple Instrument for Measuring Eye Movements", Quarterly Progress Report 62, Research Laboratory of Electronics, Massachusetts Institute of Technology, 268, 1961.

Stark, L. G. Vossius, and L. R. Young, "Predictive Control of Eye Tracking Movements", IRE Tr. on Human Factors in Electron., (1962) HFE-3,52.

Steer, R.W., Jr., "The Influence of Angular and Linear Acceleration and Thermal Stimulation on the Human Semicircular Canal", Sc.D. thesis, Massachusetts Institute of Technology, August 1967.

Steinman, R.M., "The Role of Eye Movements in Vision and in the Maintenance of Vision", presented at the Eye Movements and Psychological Process Meeting, Princeton, 1974.

Sullivan, G. and G. Weltman, "The Impedance Oculogram--a New Technique", J. Appl. Physiol., (1963) 18,215-216.

Taylor, S.E.,"The Dynamic Activity of Reading: A Model of the Process", EDL Res. and Information Bulletin (1971) McGraw Hill, New York, 9.

Thomas, E. Llewellyn, "Movements of the Eye", Sci. Amer.,(1968) 219, 88-95.

Toglia, J.O., "Electronystagmography", Diseases of the Nervous System (1973) 34,379-383.

Tokita, T., T. Fokuda and T. Watanabe, "Telemetering of Eye and Head Movements in Ballet Rotation", Aggressologie (1973) 6,21-27.

Torok, N., V. Guillemin, and J. M. Barnothy,"Photoelectric Nystagmography," Ann. Otol. Rhinol. Laryngol., (1951) 60,917.

Uenoyama, K. N. Yenoyama, and I. Iinuma, "Vector-electroculography and Its Clinical Applications", Brit. J. Ophthalmol., (1964) 48,318-330.

Vickers, D.L., "Sorcerer's Apprentice: Head Mounted Display and Wand", Ph.D. Thesis (1972), Dpet. Electrical Engineering, University of Utah, Salt Lake City, Utah. (See also Air Force AMDTR#73-1 Symposium on Visual, Coupled Systems: Development and Application , 1972).

Vossius, G.,"Das System der Augenbewegung", Z. Biol., (1960)112,27.

Westheimer, G., "Eye Movement Responses to a Horizontally Moving Visual Stimulus", AMA Arch. Ophthalmol., (1954) 52,932.

White, W J., Vision, in Bioastronautics Data Book, Webb, P., (ed.), (1964), NASA-SP-3006, 307-341.

Wolf, W. and M. Knemeyer, "Eye Movement Instrumentation", presented at the American Education Research Association Convention, February 1969.

Wheeless, L.L. Jr., R. M. Boynton and G. H. Cohen, "Eye Movement Responses to Step and Pulse-Step Stimuli", J. Opt. Soc. Am., (1966) 56,956-960.

Woellner, R.C. and A. Graybiel , "Counterrolling of the Eyes and Its Dependence on the Magnitude of Gravitational or Inertial Force Acting Laterally on the Body", J. Appl. Physiol., (1959) 14,632-634.

Yarbus, A.L., "Eye Movements and Vision", Plenum Press, New York, 1967.

Young, L.R., "The current status of Vestibular System Models", Automatica, (1969), 5, 369-383.

Young, L.R., "Recording Eye Position", Biomedical Engineering Systems, Clynes and Milsum ed., McGraw-Hill Co., New York, 1970.

Young, L.R., B. L. Zuber, and L. Stark,"Visual and Control Aspects of Saccadic Eye Movements", NASA CR-564, 1966.

Zuber, B.L., "Physiological Control of Eye Movements in Humans", Ph.D. thesis, Massachusetts Institute of Technology, 1965.

Zuber, B.L. and L. Stark, "Dynamical Characteristics of the Fusional Vergence Eye-movement System", IEEE Trans. Systems Science Cybernetics, (1968) SSC-4,72-79.

FIGURE TITLES

Figure 2.1. Typical horizontal eye movements recorded with a photoelectric monitor, showing saccadic jumps, fixation movements, smooth pursuit, and optokinetic nystagmus. From "Recording Eye Position," Biomedical Engineering Systems, Clynes & Milsum ed. Copyright 1970, McGraw Hill Book Company. Used with permission of McGraw Hill Book Company.

Figure 4.1. A method for reducing cross coupling in conjugate electro-oculography. (Young 1970 after Jeannerod et al. 1966)

Figure 4.2. Corneal Reflection Geometry

Figure 4.3. The AO Ophtalmograph. (Taylor, 1971) Courtesy of Educational Development Laboratories, A Division of McGraw Hill Book Company).

Figure 4.4. Continuous Moving Film Record of Corneal Reflections. (Taylor, 1971) Courtesy of Educational Development Laboratories, A Division of McGraw Hill Book Company.

Figure 4.5. EYE-MARKER CAMERA tracks and records the eye's glance. The image of a spot of light, reflected from the cornea, is transmitted by an optical system in the periscope through a series of prisms. This serves to superimpose the eye-marker image on the scene image. The combined image can be monitored through the viewfinder as it is photographed by the motion-picture camera. (Thomas, 1968) Copyright (1968) by Scientific American, Inc. All rights reserved.

Figure 4.6. Mobile Corneal Reflex Eye Movement Camera. (Courtesy of Polymetric Company).

Figure 4.7. Head Mounted Corneal Reflex Illumination, Viewing and Combining Optics. (Courtesy of Instrumentation Marketing Corporation).

Figure 4.8. Head Mounted Corneal Reflex System with Miniature TV Camera (Courtesy of Rees Instruments, Ltd.)

Figure 4.9. Schematic Diagram for Head Mounted TV Corneal Reflex System (Courtesy of Rees Instruments, Ltd.)

FIGURE TITLES (Continued)

Figure 4.10. TV Picture of a Bright Pupil. (Merchant and Morrissette, 1974).

Figure 4.11. Scanning Method for Tracking Limbus. (From "Recording Eye Position," Biomedical Engineering Systems, Clynes & Milsum ed. Copyright (1970), McGraw Hill Book Company. Used with permission of McGraw Hill Book Company.

Figure 4.12. Various Scan Methods Applied to Tracking the Limbus and Pupil

Figure 4.13. Differential Reflection Reading Eye Movement Measurement Device. (Courtesy of Biometrics Division, Narco Bio-Systems,Inc.)

Figure 4.14. Light and Photocell Arrangement for Limbus Tracking. (Stark et al., 1962).

Figure 4.15. Spectacle Mounted Differential Reflectivity Device. (Courtesy of Biometrics Division, Narco Bio-Systems, Inc.)

Figure 4.16. Limbus Tracking with Bifurcated Fiber Optics. (Findlay, 1974).

Figure 4.17. Tracking of the Lower Lid. (Mitrani, et al., 1972).

Figure 4.18. Tracking of Limbus Image. (Wheeless, et al., 1966).

Figure 4.19. Position of Detector Fiber Bundles on Eye Image. (Wheeless, et al., 1966).

Figure 4.20. Illumination Pattern for Two-Dimensional Limbus Tracking. (Jones, 1973).

Figure 4.21. Plane Mirror Attached to Scleral Lens. (Boyce and West, 1968).

Haptic contact lens with stalk/mirror unit attached. 0-0' optical axis; R to suction reservoir; T polyethylene tube 1/16 in.o.d.; M flat front surface mirror; P grease pad (M may be moved laterally on P for collimation purposes); S stalk 1/8 in.o.d., drilled bore 1/16 in.i.d., to allow entry of suction tube T; C corneal section of lens; L transcurves over limbus; H haptic section; D Durofix seals; U cup.

FIGURE TITLES (Continued)

Figure 4.22. Line Diagram Fixed to the Eyeball by Means of the Scleral Contact Lens. (Forgacs, et al., 1973).

Figure 4.23. The Modified Photonystagmographic Method of Forgacs. (Forgacs, et al., 197[illegible]).

The modified photonystagmographic method of Forgacs. When properly set, on the surface of the film cassette facing the lens (4) of a special camera (3) - provided with 0.1 mm wide transversal slit (6) - the magnified, sharp picture (5) of the line diagram fixed to the eyeball (1) by means of the scleral contact lens (2) is obtained. This picture is crossed by the transversal slit (6). The thick line of the line drawing is perpendicular to the slit, while the thin lines intersect it at an angle of 30°. On the film moving downwards (8) in the cassette behind the transversal slit at a constant speed of 10 mm/sec., curves in a number corresponding to the number of points of intersection between the lines of the diagram and the transversal slit are depicted as the eye moves. This set of curves makes up the photonystagmogram (7).

Figure 4.24. Photograph from Wide Angle Mackworth Camera. (Courtesy Polymetric Co.)

Figure 4.25. Illustration of a System for Recording Eye Behavior in Infants. (Haith, 1969)(Copyright (1969) by the American Psychological Association. Reprinted by Permission.)

Figure 4.26. An Illustration of a Procedure for Recording Eye-to-Eye Contact Between Mother and Child. (Haith, 1969)(Copyright (1969) by the American Psychological Association. Reprinted by Permission).

Figure 4.27. Displacement of corneal reflection from center of pupil, K Sin θ, is proportional to the angular direction, θ, of the eye, and is independent of the position of the eye. (Merchant and Morrissette, 1974).

FIGURE TITLES (Continued)

Figure 4.28. Effects of Eye Translation and Rotation on Corneal Reflection - Pupil Center (Merchant and Morrissette, 1974)

(a) Eye looking straight ahead - note corneal reflection is at center of pupil.

(b) Eye looking straight ahead but laterally displaced - note corneal reflection still at center of pupil.

(c) Eye looking to side - corneal reflection displaced horizontally from pupil center.

(d) Eye looking up - corneal reflection displaced vertically from pupil center.

Figure 4.29. Operator Indicators Superimposed on TV Image of Eye as a Function of Threshold Setting Showing Status of Measurement. Measurement is Good when Pupil is Properly Delimited. (Courtesy Whittaker Corporation).

Figure 4.30. Schematic of the Cubic Foot Remote Oculometer. (Merchant and Morrissette, 1974).

Figure 4.31. EG&G-HEL Oculometer System (Monty, 1975)

Figure 4.32. Simple Field Representation of Cornea and Rear Surface of Lens. (Cornsweet and Crane, 1972).

Location of the first and fourth Purkinje images for (a) collimated light on the eye axis and (b) collimated light at angle Δ from optic axis of the eye; EA, eye axis; FI, first Purkinje image; FH, fourth Purkinje image; L, lens; C, cornea. The dark section of arc is the equivalent mirror for the fourth Purkinje reflection.

Figure 4.33. Schematic Layout of the Double Purkinje Image Eye Tracker. (Cornsweet and Crane, 1973).

Schematic of the eye-tracker optical system: VT, visual target; R, allowed range of eye movements; IA, input axis; CA, collecting axis; CA', extension of collecting axis; S, light source; S_1, artificial pupil image at pupil of eye; CW, chopper wheel; S_2, source of Purkinje pattern, imaged at infinity; DC, dichroic mirror; M, front surface mirror; M_x and M_y, motors that drive M in x and y direction, respectively; BS, beam splitter; P_1 and P_4, quadrant photocells, A_4, aperture in front of P_4. Focal lengths of lenses L_2, L_3, and L_4 are 60, 150, and 90 mm.

FIGURE TITLES (Continued)

Figure 4.34. Apparent Ellipticity of Pupil as Eye Rotates

Figure 4.35. Scanning of Retinal Vessel. (Cornsweet, 1958).
Drawing of the optic disk, right eye. The small rectangle is the scanning spot. The dashed lines indicate the locus of its path of movement.

Figure 4.36. Fundus Tracking System. (Cornsweet, 1958).

Figure 4.37. Circular Scan X-Y Tracker

Figure 4.38. Optical Head Position Sensor (Chouet and Young, 1974).

Figure 4.39. Head Line-of-Sight Sensing System (Ferrin, 1973).

Figure 4.40. LED Line-of-Sight Head Position Measurement System. (Haywood, 1973).

Figure 4.41. Ultrasonic Head Position Measurement System. (Sawamura, 1973).

Figure 4.42. "Pipestem" Bite Board Device for Head Position Measurement Incorporated with an Eye Movement Device. (Courtesy Systems Technology, Inc.).

Figure A-1. Schematic and Optical Constants of the Eyeball. (Roth, 1968, after White, 1964 and Spector 1956).